DEPARTMENT OF COMMERCE * NATIONAL BUREAU OF STANDARDS *

NBS SPECIAL PUBLICATION 250

1982 EDITION

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Calibration and Related Measurement Services of the National Bureau of Standards

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress on March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, and the Institute for Computer Sciences and Technology.

THE NATIONAL MEASUREMENT LABORATORY provides the national system of physical and chemical and materials measurement; coordinates the system with measurement systems of other nations and furnishes essential services leading to accurate and uniform physical and chemical measurement throughout the Nation's scientific community, industry, and commerce; conducts materials research leading to improved methods of measurement, standards, and data on the properties of materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; develops, produces, and distributes Standard Reference Materials; and provides calibration services. The Laboratory consists of the following centers:

Absolute Physical Quantities[2] — Radiation Research — Chemical Physics — Analytical Chemistry — Materials Science

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Programming Science and Technology — Computer Systems Engineering.

[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Washington, DC 20234.
[2]Some divisions within the center are located at Boulder, CO 80303.

Calibration and Related Measurement Services of the National Bureau of Standards

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FOREWORD

NBS Special Publication 250 provides detailed descriptions of the currently available NBS calibration services, special test services, and measurement assurance programs. This revised edition reflects the services available as of the first quarter of 1982 and reflects a number of important changes since the 1980 Edition of SP250 was published. Future editions of SP250 will be published periodically as NBS services change.

An Appendix to SP250 is published every 6 months (April and October) that lists current prices for the services described in this publication and the NBS points of contact (addresses and phone numbers) from whom additional information can be obtained. NBS will notify users of SP250 of changes in services or proposed changes in services by means of announcements in the Appendix. In addition, information about upcoming NBS Measurement Seminars is announced there. If you are not already on our mailing list for SP250 Appendices and wish to be, fill in and return the card at the back of this document.

Many users of this publication find it convenient to keep SP250 and the current price list (Appendix) in a three-ring binder. It is important that you refer to the current issue of the Appendix in order to have up-to-date information with respect to NBS points of contact.

We call your attention to the availability of a variety of new Measurement Assurance Program (MAP) services. These are carefully designed quality control programs for critical measurements that allow the user to achieve a high level of confidence that the measurements being made in the user's laboratory are consistent with national standards and adequate for their intended use. As noted in the text, Measurement Assurance Program services are available for some traditional units (e.g., mass) and for some units associated with new technologies (e.g., laser power and energy).

The Office of Measurement Services welcomes suggestions on how this publication can be made more useful to those who rely on NBS measurement services. Suggestions are also welcome concerning needs for new calibration services, measurement assurance programs, or other measurement services.

BRIAN C. BELANGER, *Chief*
Office of Measurement Services

ABSTRACT

This publication provides descriptions of the currently available NBS calibration services, special test services, and measurement assurance programs. In addition, each section describing specific services contains references to additional publications giving more detail about the measurement techniques and procedures used. This revised edition reflects the services available as of the first quarter of 1982. NBS Special Publication 250 was last issued in 1980. The Appendix to SP250 is reissued every 6 months (April and October). It lists current prices for the services described in this publication and the NBS points of contact (addresses and phone numbers) from whom additional information can be obtained.

Key words: calibration; measurement assurance; measurement services; standards; traceability.

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Calibration and Related Measurement Services of the National Bureau of Standards

CHAPTER I

I. General Information

A. Introduction

A critical portion of the mission of the National Bureau of Standards (NBS), a major technical arm of the Department of Commerce, is to provide the basis for a complete and consistent national system of physical measurements. The Bureau accomplishes this in a variety of ways, the calibration of instruments and devices being one of the most familiar. This publication describes the measurement services that NBS provides to industry, other government agencies (Federal, State, and local), and the general public, and explains how to obtain these services. NBS does not routinely provide services to foreign organizations or individuals. Such requests are reviewed individually to determine if NBS can provide the services requested.

The calibration of standards and instruments is a widely used method of providing tie points to national standards. However, a number of other kinds of services relating to physical measurements are available, including:

(1) The broadcast of time and frequency signals
(2) Technical reports, monographs, and other publications
(3) Precision Measurement Seminars, talks, and other training aids
(4) Consultation and advisory services
(5) Use of NBS facilities in special cases*

The Bureau also provides services in areas not covered in depth by this publication (see ch. X for further details).

Those who must make precise measurements consistent with national standards have available a wide variety of NBS measurement services from which to choose. NBS staff will provide assistance to users regarding the appropriateness of particular NBS services for individual measurement problems.

The Headquarters of the National Bureau of Standards is located in Gaithersburg, MD, approximately 25 miles northwest of Washington, DC. In addition to the large office/laboratory complex in Gaithersburg, NBS maintains a major facility at Boulder, CO. Certain calibrations are performed in Gaithersburg while others are performed in Boulder. Accordingly, it is necessary to

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*Opportunity is afforded for collaborative work in the NBS facilities primarily through two programs. The Research Associate Program is a plan which enables scientists and engineers from industrial, professional, trade, and other organizations to work for specified periods (usually 1-2 years) on a full time basis under the sponsorship of their employers. Participants perform non-proprietary research compatible with NBS interests and activities. For further information, contact:

Industrial Liaison Officer
Room A402, Admin. Bldg.
National Bureau of Standards
Washington, DC 20234
(301) 921-3591

A similar program, the Guest Worker Program, permits collaboration on an individual basis not necessarily involving organizational sponsorship. As with the Research Associate program, the individual has the use of NBS facilities to pursue work benefiting NBS objectives.

determine at which location the desired calibration is available, so that your instrument or device can be shipped to the proper location. In the Appendix to this publication it is clearly indicated whether a particular calibration is performed in Boulder or in Gaithersburg.

SP 250 is available at the following places:

Superintendent of Documents, Government Printing Office, Washington, DC 20402.

Office of Measurement Services, National Bureau of Standards, Washington, DC 20234.

Field offices of the Office of Field Services, Department of Commerce.

Program Information Office, National Bureau of Standards, Boulder, CO 80303.

Federal Depository Libraries.

The Appendix listing current services and fees is issued twice yearly (April and October) and is available free from

Office of Measurement Services
National Bureau of Standards
Washington, DC 20234

Program Information Office
National Bureau of Standards
Boulder, CO 80303

B. How to Use This Publication

The chapters in this publication describing NBS measurement services are grouped according to technical disciplines, which to some extent parallel the organizational structure of NBS. An index is provided to assist in locating particular services.

The following four steps provide a checklist for obtaining a calibration service from NBS:

STEP 1: Determine whether or not an NBS calibration or measurement service is the best solution to your measurement problem. If necessary, contact the appropriate person in NBS to discuss your particular needs. (Refer to the Appendix for NBS points of contact.) For some measurement problems, the use of a Standard Reference Material, Standard Reference Data, or other NBS services may be the best solution. Upon request NBS will provide detailed information on the services described in chapter X.

Private metrology laboratories offering services to the general public can be found throughout the United States. It is not uncommon to find laboratories which, in certain areas of specialty, are capable of making measurements on a par with those made at NBS. Generally speaking, NBS' services are provided for special calibrations which are not readily available elsewhere and for calibrations which require direct reference to national standards. Accordingly, employing the services of a reputable private calibration laboratory may be a perfectly adequate and cost effective solution to many commonly encountered measurement problems. Two national organizations that can provide information regarding names and addresses of private calibration and test laboratories are:

National Conference of Standards Laboratories
c/o NCSL Secretariat
National Bureau of Standards
Boulder, CO 80303
(303) 497-3787
(Note: NCSL Directories are also available from the Office of
Measurement Services, NBS-Gaithersburg.)

American Council of Independent Laboratories, Inc.
1725 K Street NW.
Suite 301
Washington, DC 20006
(202) 887-5872

STEP 2: Having determined that an NBS calibration is warranted, the next step is to use the index in this book to find the description of the particular service of interest. If specific technical questions are not answered by the appropriate section of this book, call the telephone number

listed for that service for further information or write to the NBS technical point of contact indicated in the Appendix.

Many calibrations are listed in the fee schedule (Appendix) as being performed "At Cost." At-cost calibrations are those for which the required amount of NBS labor, materials, etc., is so variable as to make it impossible to state a fixed price. Usually a cost estimate or a range of cost can be provided over the telephone if the NBS staff member is given a description of the particular device and the desired calibration.

STEP 3: To request a calibration from NBS, read carefully the material in section C. The purchase order should be sent to either Boulder or Gaithersburg depending on the location at which the calibration is to be performed. Many users of NBS services find it convenient to schedule in advance the date of calibration by phone or letter so that the instrument or device need not be shipped to NBS until the time of its scheduled calibration approaches.

STEP 4: Prepare the instrument/device for shipping to NBS and ship. Follow the instructions in section D. *Note that the fee for calibration does not include shipping to or from NBS.*

C. Request Procedure

A formal purchase order for the calibration or test should be sent before or at the time the instrument or standard is shipped. This should provide:

1. clear identification of the device being submitted;
2. the test procedure to be followed (if not the normal NBS procedure);
3. the name and telephone number of the person in your organization responsible for this procurement;
4. the name and telephone number of a technical point of contact familiar with this request.

It should also include separate instructions for return shipment, including the matter of insurance (see sec. D), mailing of report, and billing. Requests from Federal agencies, or from State agencies, should be accompanied either by purchase order or by letter or document authorizing the cost of the work to be billed to the agency. Acceptance by NBS of purchase orders does not imply acceptance of any provisions set forth in the order contrary to the policy, practice, or regulations of the National Bureau of Standards or the U.S. Government. The purchase order should clearly state special or necessary conditions of test where appropriate (i.e., operating frequency, temperature, etc.).

Requests for measurement services should be directed to the address given in the appropriate section of the Appendix (Fees for Services), except that requests from foreign sources should be sent to the Office of Measurement Services (see sec. A for address).

D. Shipping, Insurance, and Risk of Loss

Shipment of apparatus to NBS for calibration or other tests should be made only after the customer has accepted an estimate of cost and tentative scheduling, either by telephone conversation or letter. Formal acceptance will be sent from NBS only after NBS receives the apparatus and purchase order. Repairs and adjustments on apparatus submitted should be attended to by the owner since NBS will not undertake them except by special arrangement. Apparatus not in good condition will not be calibrated. If defects are found after calibration has begun, the effort may be terminated, a report issued summarizing such information as has been found, and a fee charged in accordance with the amount of work done.

The customer should pack apparatus sent to NBS so as to minimize the likelihood of damage in shipment and handling. In every case, the sender should consider the nature of the apparatus, pack it accordingly, and clearly label shipments containing fragile instruments or materials such as glass. Care should be taken in selecting the best mode of transportation.

To minimize damage during shipment resulting from inadequate packing, the use of strong reusable containers is recommended. As an aid in preventing loss of such containers, the customer's name should be legibly and permanently marked on the outside. In order to prolong the container's use, the notation REUSABLE CONTAINER, DO NOT DESTROY should be marked on the outside.

Shipping and insurance coverage instructions should be clearly and legibly shown on the purchase order for the calibration or test. *The customer must pay shipping charges to and from NBS; shipments from NBS will be made collect.* The method of return transportation should be stated and it is recommended that return shipments be insured, since NBS will not assume liability for their loss or damage. For long-distance shipping it is found that air freight provides an advantage in reduction of time in transit. If return shipment by parcel post is requested or is a suitable mode of transportation, shipments will be prepaid by NBS but without covering insurance. When no shipping or insurance instructions are furnished, return shipment will be made by common carrier collect and uninsured.

The risk of loss or damage in handling or testing of any item by NBS is assumed by the customer, except when it is determined by the NBS that such loss or damage was occasioned solely by the negligence of NBS personnel. In such cases, the owner may apply for reimbursement.

Shipments from foreign countries which are to be transported to NBS for test, must be prearranged with a customs broker either in the country of origin or in the United States for entry of the instrument, with or without bond as may be necessary, and prepaid transportation to and from the ports of entry and exit. Entry in bond is required for all foreign made instruments shipped to NBS for calibration, whereas instruments made in the United States may be entered without bond. If arrangements are made with a broker in the country of origin the broker should, in turn, have a customs broker in or near the port of entry arrange for entry of the instrument and its transportation to the National Bureau of Standards. Direct arrangements can be made with customs brokers located in the Washington, DC/Baltimore, MD, area or the Denver, CO, area as appropriate. These brokers will arrange for entry of instruments, prepaid transportation from the port of entry to NBS, and transportation to the port of exit after measurements have been completed. Prepayment of all NBS charges is required, with respect to instruments being shipped to NBS from outside the United States.

E. Priorities and Time of Completion

Scheduled work assignments for calibrations and other tests generally will be made in the order in which confirmed requests are received. However, Government work may be given priority. For the regular services, the workload is usually such that the turnaround interval, between the date a customer's apparatus is received and the date it is prepared for return shipment, will not be more than 45 days. Some types of instruments may require a considerably longer time, particularly if their abnormal behavior requires reruns to check reliability. Others can be calibrated and returned within 10 days. The customer who can spare their instrument for only a short time usually can arrange by letter or phone call for shipping it to NBS just as their assigned starting date approaches. Generally, the acknowledgement of the purchase order gives the expected completion date.

F. Use of NBS Reports

Reports on calibrations or other services rendered to a customer are regarded as the property of the customer. Copies are not supplied to other parties except under applicable Federal law. The results set out in those reports shall not be used to indicate or imply that they are applicable to other similar items. In addition, such results must not be used to indicate or imply that NBS approves, recommends, or endorses the manufacturer, the supplier, or the user of such devices or specimens, or that NBS in any way "guarantees" the later performance of items after calibration or test.

NBS does not approve, recommend, or endorse any proprietary product or proprietary material. No reference shall be made to NBS or to reports or results furnished by NBS in any advertising or sales promotion which would indicate or imply that NBS approves, recommends, or endorses any proprietary product or proprietary material.

G. Units

The National Bureau of Standards develops and maintains the national standards of measurement including the U.S. National SI standards (for the base units, supplementary units, and numerous units derived from these). The International System of Units (SI) was defined and given

official status by the 11th General Conference of Weights and Measures, 1960. A complete listing of SI units is presented in detail in NBS Special Publication 330. SI is now the dominant system used throughout the world and its use in the United States is growing. The NBS practice is to express data in SI units unless this makes communication excessively complicated. For example, commercial gage designations, commonly used items identified by nominal dimensions, or other commercial nomenclatures or devices (such as drill sizes, or commercial standards for weights and measures) expressed in inch-pound units are an exception from this practice. However even in such instances, when practical and meaningful, SI and inch-pound units may be given in parallel. Users of NBS calibration services may specify the units to be used in the calibration, especially for commercial devices and standards using inch-pound units or units having some legal definition. For additional information on NBS metric practices and on SI see:

NBS LC1120, NBS Guidelines For Use of the Metric System

ISO—International Standard 1000, SI Units and Recommendations for Use of Their Multiples, American National Standards Institute (ANSI), 1430 Broadway, New York, NY 10018

ASTM E380-82—Standard for Metric Practice, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103 or IEEE Std. 268-82, Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, NY 10017.

Reference E380-82 or Std. 268-82 is particularly valuable since they provide precise conversion tables for conversion from customary or other units to SI. NBS Special Publication 304A, Measurement Systems, provides a brief history of measurement systems along with a chart (in color) on the basis of the modernized metric system.

For information on metric units, direct inquiries to Dr. David T. Goldman, National Bureau of Standards, Washington, DC 20234, (301) 921-3304.

H. Measurement Assurance Programs

In recent years, NBS has offered to the public a measurement service—the so-called Measurement Assurance Program ("MAP"). This section briefly explains the concept.

All measurements are made for a purpose—our health, safety, the goods we produce or use and all our technology depend on reliable measurements. It is important that the errors of measurement be small enough so that actions taken are only negligibly affected by these errors. The overall objective involves the end result of the performance of measurement systems—the quality of measurements made by systems which include instruments, operators, environments in which they function, procedures, and special characteristics of the objects being measured. One must always carefully distinguish *system* performance from *element* performance—that is, the performance of an instrument, operator, or any other single element of the system. Adequate instrument performance is a necessary condition for adequate system performance but obviously it cannot be a sufficient condition. It is the performance of instruments under actual practical conditions of use which must be considered in approaching the problem of adequacy of the measurement effort.

It is essential to recognize that when the quality of measurements is at issue, standardization must take into account all factors influencing the uncertainty of measurements. The uncertainty of measurements will, in general, depend on the instruments, the environment in which they are used, the procedures used, the training of the operator, the treatment of measurement data, and other factors. It must be remembered that uncertainty is a property of measurements—it is not a property of instruments.

Measurement assurance (like quality control in industrial production) is a means by which one determines that whatever errors occur in the measurement process are kept sufficiently small to be adequate to the need. There are several elements in a measurement assurance program:

° It has its beginning in a requirement on the limit of measurement error which can be tolerated (e.g., radioactivity to $\pm 1\%$)

° There must be a reference base to which the allowable error is referred (e.g., NBS Volt, NBS Kilogram)

° There must be documented technical proof of measurement uncertainty

- There must be some continuing redundancy in the system so that one is able to "sample" the quality of the measurements being made (e.g., by remeasuring a test item, or by the use of well characterized artifacts).

This redundancy should be truly indicative of system performance. If a test item is used for routine checking, it should have the characteristics of the regular workload and should be run at intervals sufficiently large to permit a full range of the factors which cause random variation.

The importance of continuing verification that the measurements are "in control" is obvious in regulatory situations where action may be taken on the basis of only a few measurements. In any disagreement one would have to show that the system had predictability—i.e., that the announced error limits were applicable at the time of measurement.

NBS provides the users of these services a means by which the offset of their measurement process relative to the national reference unit can be determined. Usually this involves on-site measurements of an NBS transport standard or suitable artifact so that all elements of the users process are involved (not just the standard as is the case when the instrument is shipped to NBS for calibration).

All who measure need to know that the errors of their measurement relative to the accepted reference are less than the allowable limit. The procedures by which this is achieved constitute a measurement assurance program whether it be the result of extensive redundancy or from performance data from produced items or similar measures of operational success.

Currently available NBS Measurement Assurance Program services are described in the main body of the text of this publication.

I. Classification of NBS Measurement Services

NBS has recently imposed new Bureau-wide quality control requirements for all services described in this publication and listed in the Appendix (this excludes miscellaneous services listed in chapter X). These NBS services will henceforth be categorized as Calibrations, Measurement Assurance Programs, or Special Tests.

1. Criteria for Calibration or Measurement Assurance Program (MAP) Services

A service must conform to all of the following criteria in order to be listed in SP250 as a "Calibration Service" or "MAP Service."

(A) The calibration or MAP service is a regularly performed service with pre-established and well-defined conditions.

(B) The measurement process is well-characterized and shown to be stable and predictable. The variation in performance of individual devices being calibrated must not exceed pre-established limits, i.e., NBS calibrates only devices known to be suitable as reference or transfer standards.

(C) Quality assurance procedures (explicit) are in place and followed.

(D) Thorough documentation and a long-range plan are available.

New calibration services are not approved until they meet these criteria. Existing calibration services are required to meet these criteria as soon as possible but by the end of Fiscal Year 1986 (September 30, 1986) at the latest.

2. Criteria for Special Tests

Any service that meets one or more of the following criteria will be listed in SP250 as a "Special Test."

(A) One-of-a-kind or seldom-calibrated items, the workload of which does not justify the characterization of the measurements as a process (e.g., pooled statistics cannot be used, check standards representative of the items being calibrated are not available, etc.).

(B) Special tests requested by clients.

(C) Measurement or calibration methods for which refinements and/or modifications are still expected.

J. Traceability

Traceability is a term which has been invoked to specify the standards used in the calibration of instruments.

Perhaps the first and most far-reaching traceability requirement has been that of the Department of Defense MIL-STD-45662, "Calibration Systems Requirements," which states (sec. 5.7.1):

"Measuring and test equipment shall be calibrated by the contractor or a commercial facility utilizing standards whose calibration is certified as being traceable to the National Standards, has been derived from accepted values of natural physical constants, or has been derived by the ratio type of self-calibration techniques."

This specification defines the term "traceability" as: "The ability to relate individual measurement results to national standards or nationally accepted measurement systems through an unbroken chain of comparisons."

NBS can provide technical advice on how to make measurements consistent with national standards, but NBS cannot state what must be done to comply with a contract or regulation calling for "traceability to National Standards" to which NBS is not a party. For additional information on traceability and its implications, refer to "Traceability: An Evolving Concept," B. C. Belanger, *ASTM Standardization News,* Vol. 8, No. 1, January 1980, pp. 22–28. (Reprints available from the NBS Office of Measurement Services.)

K. Policy on Fees for Services

The basic Congressional directive concerning charges to the public for services is stated in 31 U.S.C. 483a, reading in part:

"It is the sense of the Congress that any work, service, publication, report, document, benefit, privilege, authority, use, franchise, license, permit, certificate, registration, or similar thing of value or utility performed, furnished, provided, granted, prepared, or issued by any Federal agency...to or for any person (including groups, associations, organizations, partnerships, corporations, or businesses)...shall be self-sustaining to the full extent possible..."

Services for which charges are to be made are those which provide special benefits to individuals and small segments of the public above and beyond those which accrue to the general public. Special benefits obviously accrue in the case of calibration services.

A number of guidelines have been set up in Department of Commerce Administrative Order 203-5, dated August 20, 1973, as amended, including the following:

- Department of Commerce policy is to recover full cost of performing a special service, not the value to the recipient.
- However, charges or fees should not be established if they would seriously impair the objectives of programs or are against public policy.
- Department policy is to refuse to furnish special services to individuals, groups, or companies when the service would be considered in competition with commercial enterprise.

Cost elements for inclusion in charges to the public should include but not be limited to:

- Direct costs, such as labor, accrued leave factor, personnel benefits, supplies, etc.
- Direct and indirect supervisory costs
- Overheads, including supporting services, depreciation on equipment, maintenance, etc.

Calculations of fees for NBS calibrations are based on the above guidelines.

L. Legislative Authority

Part 200, Title 15, of the Code of Federal Regulations, states the legislative authority for and describes the measurement services NBS provides to the public.

The recognition of the need for a consistent measurement system led to the formation of the National Bureau of Standards and in particular to the responsibility (15 U.S.C. 272(a)) for "The custody, maintenance, and development of the national standards of measurement, and the

provision of means and methods for making measurements consistent with those standards, including the comparison of standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government."

Section 2 of the NBS Organic Act (15 U.S.C. 272) authorizes the undertaking of various activities related to calibration and measurement when the need arises in the operations of Government agencies, scientific institutions, and industrial enterprises, including the testing and calibration of standards and of standard measuring apparatus; the study and improvement of instruments and methods of measurements; and the compilation and publication of general scientific and technical data resulting from the performance of the functions specified in the Organic Act or from other sources when such data are of importance to scientific or manufacturing interests or to the general public, and are not available elsewhere.

CHAPTER II

II. Dimensional Measurements

The National Bureau of Standards has established a number of realizations of the length unit relative to the international definition of length in terms of the wavelength of radiation from a Krypton source. This section describes the services available to those needing tie points to the measurement system maintained by the Bureau.

A. Length

Length measurement services offered by NBS are intended to serve several purposes: (1) to disseminate the length unit to the industrial and scientific community, (2) to offer guidance in establishing measurement assurance programs in length, (3) to provide assistance where there are special problems in measurement techniques, or where extreme accuracy requirements exist, and (4) to resolve disagreements between parties involving length measurements.

Arrangements for Calibration or Test

Charges for services in length are listed "At Cost" in the Appendix. Upon receipt of a request for services an estimated cost will be given along with a firm date for completion. An effort will be made to discuss the measurement requirement with the customer so as to give proper service at minimum cost and delay.

1. Gage Blocks

All gage blocks submitted for test should be in substantially new block condition and each block should be marked with an identification number.

In shipping gage blocks, extreme care should be taken both against corrosion and damage by contact with other gage blocks. All defining steel surfaces should be greased and the blocks padded with waxed paper or volatile rust inhibitor treated paper. A greased steel surface coming in contact with newspaper, wrapping paper (unwaxed), or excelsior is very likely to corrode. Sets of gage blocks should have packing inside the case and the case should be bound shut as the clasps open or break frequently during shipment.

References

[1] **Measurement assurance for gage blocks,** C. Croarkin, J. Beers, and C. Tucker, *Natl. Bur. Stand. (U.S.), Monogr. 163,* 75 pages (Feb. 1979).

[2] **Measurement assurance program—A case study: Length measurements. Part 1. Long gage blocks (5 in to 20 in),** P. E. Pontius, *Natl. Bur. Stand. (U.S.), Monogr. 149,* 75 pages (Nov. 1975).

[3] **Gage block flatness and parallelism measurement,** J. S. Beers and C. D. Tucker, *NBSIR 73-239,* 12 pages (Aug. 1973). Order from NTIS as PB273962.

[4] **Intercomparison procedures for gage blocks using electromechanical comparators,** J. S. Beers and C. D. Tucker, *NBSIR 76-979,* 23 pages (Jan. 1976). Order from NTIS as PB248992.

[5] **A gage block measurement process using single wavelength interferometry,** J. S. Beers, *Natl. Bur. Stand. (U.S.), Monogr. 152,* 34 pages (Dec. 1975).

[6] **Preparations for gage block comparison measurements,** C. D. Tucker, *NBSIR 74-523,* 14 pages (July 1974). Order from NTIS as COM 75-11126.

2. Linear Thermal Expansion of Length Standards

A coefficient of linear thermal expansion will be determined for length standards such as gage blocks and line scales only where the manufacturer's stated value is inadequate or unknown. Coefficients will be determined in a temperature range near 20 °C (68 °F).

3. Gage Block Comparator Stylus Tip Radius

If gage blocks of different materials are being compared it is important to know the stylus tip radius so a penetration correction can be determined. Tips received for measurement will be examined for flaws and imperfect geometry. Only tips which are spherical in the contact area and are free from cracks and chips will be measured because imperfections prevent predictable performance.

Reference

[1] **Contact deformation in gage block comparisons,** J. S. Beers and J. E. Taylor, *Natl. Bur. Stand. (U.S.), Tech. Note 962,* 46 pages (May 1978).

4. Line Standards of Length

Graduated scales up to 6 m (20 ft) in length and having suitable graduations and cross-sectional shapes will be measured interferometrically. The length values will be reported at 20 °C (68 °F).

5. Surveying and Oil Gaging Tapes

The calibration of surveying tapes and oil gaging tapes will be made with the tape under tension and supported on a horizontal flat surface in a laboratory controlled near 20 °C (68 °F). Unless otherwise requested, the total length and each 50 ft or 15 m subinterval will be measured and reported at 20 °C (68 °F). For oil gaging tapes the height from the tip of the plumb bob will also be reported at 60 °F.

Each interval calibrated on a surveying tape will have a table of computed lengths for two (single catenary), three, four, and five equidistant points of support. The computed values will be based on the measured lengths and the average values for weight per unit length and AE (cross-section area of tape times modulus of elasticity) determined during the test and given in the report.

The following thermal expansion coefficients will be assumed unless another value is provided by the customer or the tape manufacturer:

Steel:	0.0000116/°C (0.00000645/°F)
Stainless:	0.0000106/°C (0.00000589/°F)
Invar:	0.0000004/°C (0.00000022/°F)

Horizontal tension will be applied to the tapes by weights hanging from a pulley device. For various materials and lengths of tapes the following weights will be used in the calibration:

	Equal or less than		Longer than	
Material	30m	100 ft	30m	100 ft
steel	5 kg	10 lb	10 kg	20 lb
stainless	5 kg	10 lb	10 kg	20 lb
Invar	15 kg	20 lb	15 kg	20 lb

An NBS serial number will be engraved on each calibrated tape for identification.

6. Surveying Leveling Rods

Surveying leveling rods having invar graduated strips will be calibrated in a laboratory controlled near 20 °C (68 °F). The 1-, 2-, and 3-meter intervals will be measured from a zero point on the footpiece established by the intersection of the centerline of the invar strip with the plane of the bottom of the footpiece. A thermal expansion coefficient of 0.0000015/°C will be assumed for the invar strip unless another value is provided by the customer or the manufacturer. The lengths of the intervals will be reported at 20 °C unless otherwise requested.

An automated calibration process is also available for high-quality leveling rods in good condition. Every scale interval is measured from a zero point on the footpiece, established as described above. A photoelectric edge detecting microscope is used to locate graduation edges and a laser interferometer provides the length standard. Reduced data are reported in a written report, on a digital magnetic tape, or in graphical form.

7. Sieves

Sieves in the size range from No. 3-1/2 to No. 400 will be tested for conformity to the dimensional requirements of ASTM specifications (Designation E11-70). An NBS Seal and identification number will be marked on all sieves conforming to the specification.

An alternate calibration method is the sieving test which can be performed with the Standard Reference Materials listed in the table below.

Glass spheres for particle size

SRM*	Type	Size (μm)	Sieve Nos.	Wt/unit (g)
1003	Calibrated Glass Spheres	5-30	--	40-45
1004	Calibrated Glass Beads	34-120	400-140	63
1017a	Calibrated Glass Beads	100-310	140-50	84
1018a	Calibrated Glass Beads	225-780	60-25	74
1019	Glass Spheres	890-2590	18-8	100

*See section on Standard Reference Materials (ch. X) for ordering procedure.

8. Haemacytometers

Each haemacytometer chamber and each cover glass which conforms to the specification is marked with a National Bureau of Standards precision seal.

9. Precision Circles

Graduated circles or encoder discs having suitable graduations and being not less than 50 mm (2 in) in diameter will be tested for maximum angular error in the mean of opposite angles.

B. Dimensional Metrology

For controlling dimensions in the manufacture of all products, various types of dimensional gages are used. Gages which are used for precise size control of critical dimensions are measured in our laboratories as a service to the public. The wide variety of such gages measured includes end standards for length, cylindrical plug and ring gages and balls for diameter, and screw thread gages. Angle gage blocks, polygons, angular indexing tables, and other such items are calibrated for controlling angular dimensions. In addition, various instruments, measuring tools, and accessories are calibrated such as optical flats for measuring flatness, cylinders used for the measurement of threads and gears, and many other specialized components. Consultation services with respect to dimensional and angular measuring problems are available also.

The length and diameter standards and gages, with the exception of thread and gear measuring wires, are in general intended to be used as comparison masters. In addition to the items listed, high quality components requiring gage tolerance inspection of length or diameter may be calibrated as special measurements. In addition to the items listed in the Appendix, other items such as gage block accessories and Knoop indenters are calibrated upon special request. Sizes other than those listed in the fee schedules also are calibrated on special request.

A three-axis measuring machine is available for calibrating two- and three-dimensional ball plates, glass grid plates and other devices of complex shape. The machine, built to state-of-the-art specifications, is housed in a stabilized environment and can be operated either manually or under full computer control. It has a working volume of $48 \times 24 \times 12$ in and can detect a length difference of 0.013 μm (0.5 μin). Bulk disc storage of computer programs is provided and plotters

capable of graphic presentation are available. The machine will provide digital data in three dimensions or two-dimensional graphic projections of complex three-dimensional shapes. Reference to the standard of length is insured by laser interferometry.

References

[1] **On characterizing measuring machine geometry,** R. J. Hocken and B. R. Borchardt, *NBSIR 79-1752* (May 1979).

[2] **Three dimensional metrology,** R. Hocken, J. Simpson et al., *Annals of the CIRP,* Vol. 26-1, 1977.

[3] **Unified three-dimensional program—Two useful noncontacting probes,** J. A. Simpson, *NBS Report 10597* (May 1971).

Shipping Instructions

In the shipment of gages, extreme precautions should be taken against both corrosion and damage by contact with other gages during transit. All defining steel surfaces should be greased and protected with rust inhibiting paper or a suitable strippable plastic coating. A greased steel surface coming in contact with newspaper, untreated wrapping paper, or excelsior is very likely to corrode. Small gages suitably wrapped may be fastened in place in a strong container so that no movement is possible. Plug and ring gages ordinarily should not be shipped mated. In the case of large-size threaded plugs and rings, however, mating is permissible as a means of protecting the plug threads. In such cases, a grease must be used that will prevent corrosion between the mating gages.

1. End Standards of Length

The listed end standards, having spherical, flat, or pointed ends normally are used as instrument or machine tool setting standards. End standards up to 20 ft in length can be calibrated. As a special test, end measuring bars with flat ends of gage block quality can be calibrated to a higher accuracy. Lengths are reported with a 2.5 lb measuring force unless otherwise requested.

2. Step Gage Standards of Length

Step gages having flat parallel faces along a common center line are calibrated as special measurements. The test is made horizontally in lengths up to 40 in. Step blocks having flat parallel adjacent faces also are calibrated as special measurements.

3. External Diameter Standards and Gages: Plug Gages

In addition to the scheduled plug and wire gages, external diameters of other products may be accepted for measurement.

4. Measuring Wires for Threads and Gears

Thread measuring wires for 60° and 29° threads are tested for compliance with the latest specifications in commercial use given in NBS Handbook H-28 and American National Standards Institute, Inc. Standard B1.2. These wires, which are supplied in 3-wire sets, are calibrated and the pitch diameter correction factor is computed for the average diameter of the 3 wires in the set. Special thread measuring wires for unusual sizes and for threads finer than 80 tpi are measured in a manner consistent with current commercial practice as a special test. Gear measuring wires in the 1·92″/P, 1·728″/P, 1·44″/P, and 1·68″/P series supplied in sets of 2 wires are tested for compliance with the latest specifications in commercial use and the mean diameter reported. Reference master wires for threads and gears are supplied as single wires which are intended as transfer standards of diameter for the calibration of working sets of thread measuring and gear measuring wires. Wires are measured using standard measuring practice.

Reference

[1] **On the measurement of thread measuring wires,** B. N. Norden, *NBS Report 10987* (Jan. 1973).

5. Spherical Diameter Standards: Balls

Balls used in precision bearings and master balls used as transfer diameter standards are calibrated according to current commerical practice. The ball diameters reported are the undeformed sizes as calculated with the Hertz relations to maintain a consistency in reported sizes.

6. Internal Diameter Standards: Ring Gages

In addition to ring gages, holes in precision products can be calibrated as special measurements.

7. Plain Conical Plug and Ring Gages

Plain conical plug and ring gages are tested for angle and diameter at a specified position.

8. Threaded Plug and Ring Gages

Threaded plug and ring gage calibrations are limited to those gages conforming to current American Petroleum Institute (API) specifications. API regional master and reference master thread gages are tested as required by API Standards 5B, 7, and 11B. The gages must be marked with the API monogram and the API registration number. If not so marked, the gages will be returned to the customer uncalibrated. Gages which meet the specifications will be marked as specified in the API standards. All thread gages must be submitted in sets of plug and ring. The name of the gage owner should be given for inclusion in the report. Copies of all reports are sent to the American Petroleum Institute. API standards may be obtained from the American Petroleum Institute, 211 N. Ervay, Suite 1700, Dallas, TX 75201. Fee is for single set of plug and ring.

9. Length and Diameter Measuring Instruments

Micrometer calipers, vernier calipers, plain snap gages, micrometer screws, dial micrometers, vernier calipers, and other similar devices are accepted for calibration only under special circumstances.

10. Length Measuring Elements

Length measuring elements such as micrometer screws, dial micrometers, and other length-transducing systems are accepted for calibration only under special circumstances.

11. Instrument Components Requiring Dimensional Control

Some instruments such as penetration needles, polariscope tubes, and Knoop indenters contain elements which require dimensional control of lengths and angles.

Penetration needles and cones are tested for compliance with ASTM specifications and supplied with individual labels so stating. All needles must have individual identification numbers; needles received without identification will be returned to the customer untested.

C. Flatness, Roundness, and Angular Measurements

This section deals with the calibration of reference surfaces of flatness and straightness, such as optical flats, surface plates, and straight edges.

1. Optical Reference Planes: Flats

Optical reference planes are tested interferometrically, horizontally supported with test surface supported on three equally spaced pads located at 0.7 of the radius from the center. The measurement is performed along two marked diameters at 90° to each other on each surface when each diameter is parallel to two of the support pads.

References

[1] **A survey of the stability of optical flats,** C. P. Reeve and R. C. Veale, *NBSIR 73-232,* 27 pages (June 1973). Order from NTIS as PB273947.

[2] **The calibration of an optical flat by interferometric comparison to a master optical flat,** C. P. Reeve, *NBSIR 75-975,* 40 pages (Dec. 1975). Order from NTIS as PB253113.

2. Surface Plates and Straight Edges

The straightness of specified lines on surface plates and the straightness of straight edges are calibrated by optical and mechanical techniques.

3. Roundness

In addition to the measurement of the deviation from roundness of round parts, instrument calibration standards for roundness measurement equipment can be calibrated.

4. Roundness Measurement

The deviation from roundness at eight or more specific positions around nominally round standards is determined. The size of the calibration step or deviation from roundness on calibration standards is determined. The departure from roundness of components and gages is measured and the results are reported in graphical form.

5. Angular Standards

Fixed angular standards having flat defining surfaces are calibrated by autocollimation and interferometric techniques. Angle gage blocks are calibrated using autocollimation techniques.

The calibration of polygons is done with autocollimation techniques. It consists of the determination of flatness of each face, variation of the angle between each face and the base (where possible the polygon will be adjusted for minimum variation), and the angle between faces.

The solid angle calipers and step mirrors are calibrated by autocollimation or interferometric techniques as to the angle between faces. Wedges are calibrated by autocollimating or interferometric techniques at a specified wavelength for deviation angle.

Mechanical angular references such as cylindrical squares and machinist's squares usually are calibrated by mechanical techniques.

Reference

[1] **A survey of the temporal stability of angle blocks,** R. C. Veale and C. P. Reeve, *NBSIR 74-601,* 22 pages (Nov. 1974). Order from NTIS as PB273948.

6. Angular Measuring and Setting Instruments

Instruments and tools used for the precise measurement of angle, such as precision angular rotary and indexing tables, autocollimating telescopes, or angle generating equipment, are calibrated at specific angular settings.

Reference

[1] **The calibration of indexing tables by subdivision,** C. P. Reeve, NBSIR 75-750, 38 pages (July 1975). Order from NTIS as PB249934.

D. Surface Texture

Precision surface roughness specimens and test measurements on other surface finishes can be made in accordance with American National Standards Institute, Inc. Standard B-46.1 (1978). Since 1 July 1973, these measurements are made with an interferometrically calibrated minicomputer/stylus instrument system rather than by comparisons against master specimens. (See ref. [6] and ref. [10].)

1. Instrument Calibration Specimens

Instrument calibration specimens for surface roughness measuring equipment having regular geometrical surface profiles are calibrated with the use of the interferometrically calibrated minicomputer/stylus instrument system (see ref. [6].)

2. Surface Roughness Measurements

Roughness measurement of roughness comparison specimens or of other surfaces are measured in accordance with American National Standards Institute, Inc. Standard B-46.1, using our instrumentation.

3. Step Height Measurements

Thin film step heights are measured with the use of the minicomputer/stylus instrument system and interferometrically calibrated reference step heights (see ref. [6].)

References

[1] **Surface microtopography,** R. D. Young, *Phys. Today* **24,** No. 11, 42-49 (Nov. 1971).

[2] **Precision reference specimens of surface roughness: Some characteristics of the Cali-Block,** R. D. Young and F. E. Scire, *J. Res. Natl. Bur. Stand. (U.S.),* **76C** (Eng. and Instr.), Nos. 1 and 2, 21-23 (Jan.-June 1972).

[3] **Eight techniques for the optical measurement of surface roughness,** R. D. Young, *Natl. Bur. Stand. (U.S.), NBSIR 73-219,* 38 pages (May 1973).

[4] **Surface finish, friction and wear; the need for more than one parameter,** D. A. Swyt, *Natl. Bur. Stand. (U.S.), NBSIR 73-196,* 28 pages (May 1973).

[5] **Evaluation, revision and application of the NBS stylus/computer system for surface roughness measurement: Minicomputer software,** E. C. Teague, *Natl. Bur. Stand. (U.S.), NBSIR 75-924,* 79 pages (Apr. 1975).

[6] **Evaluation, revision and application of the NBS stylus/computer system for the measurement of surface roughness,** E. C. Teague, *Natl. Bur. Stand. (U.S.), Tech. Note 902,* 151 pages (Apr. 1976).

[7] **Surface finish measurements: An overview,** E. C. Teague, *Soc. Manuf. Eng. Tech. Pap.* **IQ75-137,** 1-21 (1975).

[8] **The measurement and characterization of surface finish,** R. D. Young and E. C. Teague, Chapter 2 in *Properties of Electrodeposits, Their Measurement and Significance,* R. Sard, H. Leidheiser, and F. Ogburn, Eds., pp. 22-49 (Electrochemical Society, Princeton, NJ, 1975).

[9] **Measurements of stylus radii,** T. V. Vorburger, E. C. Teague, F. E. Scire, and F. W. Rasberry, *Wear* **57,** 39-49 (1979).

[10] **FAST facility available for engineering needs,** T. V. Vorburger, E. C. Teague, and F. E. Scire, *Dimensions/NBS 62,* 18-20 (Nov. 1978).

E. Volume and Density

NBS calibrations of glass and metal volumetric reference standards and of reference standard hydrometers, and density determinations of solids and liquids, are offered only if suitable service is not available otherwise. In order to provide prompt and useful service, the acceptance of the items for calibration or test is based on discussions with each user to determine details necessary to meet measurement and delivery requirements, and on inspection of the item at the Bureau with reference to its suitability for the usage intended. The section in the Appendix entitled "Volume and Density" lists the most common services. The services are not limited to these specific items and inquiries are invited concerning other measurement problems in the above areas.

Services are available to enable a user to establish a measurement assurance program for certain measuremnt processes. This may involve developing procedures for establishing and maintaining a state of statistical control for the measurements, the determination of the offset of the process from the national system, and assisting in the determination of the uncertainty of measurements made by the user's process.

Arrangements for Calibration or Test

Arrangements for calibration (or test) must be completed before shipping apparatus to the Bureau. While all of the services related to volume and density are on an actual cost basis, subject to a $25 minimum charge, a mutual agreement on the work to be performed generally results in substantial savings for the user. Detailed packing and shipping instructions are available on request. Items not accepted for calibration or test will be returned, the cost of inspection or the minimum charge will be applicable.

The results of a calibration or test will be reported either in a National Bureau of Standards Report of Calibration or of Special Test, continuation report, or a letter report. In each of these, the values reported are accompanied by an appropriate estimate of uncertainty (allowance for random and systematic errors) as determined by an analysis of the specific measurement process. A continuation report is used for those items submitted for recalibration on which preliminary tests indicate that no significant changes have occurred since the last calibration. Usually a letter report is used to report a test for compliance with a specification which states limits for the departure of the actual value from nominal.

Charges for these services are listed "At Cost." Upon receipt of a request for services, an estimated cost will be given along with a firm date for completion. An effort will be made to discuss the measurement requirement with the customer so as to give proper service at minimum cost and delay.

1. Reference Standards of Volumetric Apparatus

The procedure used almost universally for testing glass volumetric apparatus is to weigh the amount of distilled water contained or delivered with reference to the graduations marked on the instrument, the volume being computed from the density of the water (for tables see NBS Circular 19, available on request). The quality of the markings and the care exercised in reading or setting the liquid level are major factors in test calibration and usage. Normally the Bureau will accept instruments for calibration which have volumes in the range 1 ml to 1 gal and which conform essentially to requirements contained in NBS Circular 602, "Testing of Glass Volumetric Apparatus," Federal Procurement Specifications NNN-B-00789 (Buret, straight, precision), NNN-F-00289a (Pipet, volumetric), NNN-P-0035a (Pipet measuring), or NNN-F-00289a (Flask, volumetric), if such instruments are to be used as reference or transfer standards.

The following comments relate to commonly used volumetric apparatus:

° Suggested test procedures for the verification of the compliance of precision grade glassware with specifications and tolerances are available on request.

° The usual calibration procedure for metal volumetric apparatus consists of determining the value "to contain" or "to deliver" by either gravimetric means or by the use of transfer standards. Normally the Bureau will accept instruments for calibration which have values in the range 1 gill to 1000 gal, which comply essentially with the specifications contained in NBS Monograph 62, "Testing of Volumetric Standards," and which are free from dents, bumps, or scratches.

° While it is preferred that the zero index or the gage scale be adjusted and scaled prior to calibration, these operations can be incorporated into the calibration procedure if requested. Slicker plate type standards should be adjusted by the manufacturer.

References

[1] **Procedures for the calibration of volumetric test measures,** J. F. Houser, *NBSIR 73-287,* 24 pages (Aug. 1973). Order from NTIS as COM 73-11928.

[2] **Calibration of small volumetric laboratory glassware,** J. Lembeck, *NBSIR 74-461,* 34 pages (Oct. 1974). Order from NTIS as PB246623.

[3] **The equivalence of gravimetric and volumetric test measure calibration,** R. M. Schoonover, *NBSIR 74-454,* 16 pages (Feb. 1974). Order from NTIS as COM 74-10988.

The usual procedure for determining the density of solids is by classical hydrostatic weighing or by an immersed balance technique. At the Bureau liquid densities usually are determined by gravimetric methods. Other methods are available depending on the requirements. The Bureau will accept requests for density determinations if the need is critical, as in the support of scientific studies or standard sample programs. Limitations on the mass, physical dimensions, or volume of the sample are available on request.

Specific gravity hydrometers covering the range 0.62 to 3 and proof spirit hydrometers in the range 0 to 200 proof, which are designed and used as reference standard hydrometers (used to test other hydrometers), normally are accepted for calibration. A limited number of other types of reference standard hydrometers will be accepted for multipoint calibration subject to a discussion of detailed requests. Instruments accepted must comply essentially with the requirements of NBS Circular 555, "Testing of Hydrometers."

References

[1] **A density scale based on solid objects,** H. A. Bowman, R. M. Schoonover, and C. L. Carroll, *J. Res. Natl. Bur. Stand. (U.S.),* **78A** (Phys. and Chem.), No. 1, 13-40 (Jan.-Feb. 1974).

[2] **Reevaluation of the densities of the four NBS silicon crystal standards,** H. A. Bowman, R. M. Schoonover, and C. L. Carroll, *NBSIR 75-768,* 36 pages (Aug. 1975). Order from NTIS as PB247943.

[3] **The utilization of solid objects as reference standards in density measurements,** H. A. Bowman, R. M. Schoonover, and C. L. Carroll, *Metrologia* **10,** 117-121 (1974).

[4] **Quick and accurate density determination of laboratory weights,** R. M. Schoonover and R. S. Davis, (Proc. 8th Conf. IMEKO Technical Committee TC3 on Measurement of Force and Mass, Krakow, Poland, Sept. 9-11, 1980). Paper in *Weighing Technology,* pp. 1123-1127 (Druk, Zaklad Poligraficzny Wydawnictwa SIGMA, Warszawa, Poland, 1980). Reprints available from NBS as required.

CHAPTER III

III. Mechanics

That broad area of the physical sciences generally prescribed by the action of forces on bodies, materials and matter is quantified through measurements based on mass, length, and time. Length and mass are the capstones of this measurement system usually characterized by the discipline of mechanics. In addition to the base units of mass and length, a wide range of derived quantities and multiples or submultiples of all these units are employed by science and technology to implement the affairs of industry, commerce, and government. Among the mechanics-related derived quantities maintained and disseminated by NBS are force, volume flowrates, air and water velocity, acoustic quantities, and vibration. Well-characterized instruments are compared with these standards through calibrations and measurement assurance programs to provide measurement traceability and to ascertain the quality of measurements in the field. Supporting research and development programs are conducted to extend the range and quality of these types of measurement and to increase the efficiency of the measurement system.

A. Mass

The National Bureau of Standards maintains the national standards for mass in the form of the prototype kilograms (K4 and K20) and provides services to support the segments of the national measurement system which rely directly or indirectly on mass measurements. These services are offered only if suitable service is not available otherwise. In order to provide prompt and useful service, the acceptance of the items for calibration or test is based on discussions with each user to determine details necessary to meet measurement and delivery requirements, and on inspection of the item at the Bureau with reference to its suitability for the usage intended.

Services are available to enable a user to establish a measurement assurance program for certain measurement processes. This may involve developing procedures for establishing and maintaining a state of statistical control for the measurements, the determination of the offset of the process from the national system, and assisting in the determination of the uncertainty of measurements made by the user's process.

Arrangements for calibration (or test) must be completed before shipping apparatus to the Bureau. While all services are on an actual-cost basis, subject to a $25 minimum charge, a mutual agreement on the work to be performed generally results in substantial savings for the user. Detailed packing and shipping instructions are available on request. Items not accepted for calibration or test will be returned, the cost of inspection or the minimum charge will be applicable.

The results of a calibration or test will be reported in a National Bureau of Standards Report of Test or of Special Test (which in many cases is prepared by a computer program), a continuation report, or a letter report. In each of these, the values reported are accompanied by an appropriate estimate of uncertainty (allowance for random and systematic errors) as determined by an analysis of the specific measurement process. A continuation report is used for those items submitted for recalibration on which prelimiary tests indicate that no significant changes have occurred since the last calibration. Usually a letter report is used to report a test for compliance with a specification which states limits for the departure of the actual value from nominal.

Charges for these services are listed "At Cost." Upon receipt of a request for services, an estimated cost will be given along with a firm date for completion. An effort will be made to discuss the measurement requirement with the customer so as to give proper service at minimum cost and delay.

The Bureau's calibration of reference standards of mass provides extensions of the mass unit embodied in the NBS standards of mass. A normal calibration consists of establishing a mass value

and the appropriate uncertainty for that value for each weight which has been designated to be a reference standard. It is desirable, but not necessary, that a weight meet the adjustment tolerances established for Classes A, B, M, or S-1 prior to submission. Normally weights are available from manufacturers, many of whom can furnish directly documentation suitable for meeting quality assurance contracts and requirements.

Individual weights or sets of weights in the range of 30 kg to 1 mg or 50 lb to 1 μlb in decimal subdivisions, which are designated as reference standards, must be of design, material, and surface finish comparable to but not necessarily limited to present Classes A, B, M, S, or S-1. Design, material, and surface finish of large mass standards (over 50 to 50,000 lb) must be compatible with the intended usage. For these large mass standards an adjustment with reference to a nominal or desired value can be included as a part of the calibration procedure.

The values of true mass (and an apparent mass correction) included in the report will be determined by using computed volumes based on the manufacurer's statement of density of the material, on the density computed from measured volumes, or, in the absence of this information, on estimated density values. The apparent mass corrections are computed for 20 °C with reference to Normal Brass (density 8.4 g/cm^3 at 0 °C, volume coefficient of expansion 0.000054/°C) and to stainless steel (density 8.0 g/cm^3 at 0 °C, volume coefficient of expansion 0.000045/°C) in an ideal air density of 1.2 mg/cm^3. Apparent mass corrections to any other basis can be furnished if requested.

For periodic recalibrations of reference mass standards, the user need measure only differences between weights or groups of weights within a set and compare them with computed differences. As long as the agreement is within allowable limits, the values can be considered constant within the precision of the comparison process. Mass standards which are submitted to the Bureau for recalibration frequently are tested in this manner. If these tests indicate that no significant changes have occurred, a continuation report so stating and referring to the previous NBS Report of Calibration will be issued.

References

[1] **Measurement philosophy of the pilot program for mass calibration,** P. E. Pontius, *Natl. Bur. Stand. (U.S.), Tech. Note 288,* 41 pages (May 1966).

[2] **Introduction to intercomparison methods in mass measurement,** H. E. Almer, *Natl. Bur. Stand. (U.S.) Report 9487,* 15 pages (Feb. 1967).

[3] **Realistic uncertainties and the mass measurement process,** P. E. Pontius and J. M. Cameron, *Natl. Bur. Stand. (U.S.), Monogr. 103,* 18 pages (Aug. 1967).

[4] **Method of calibrating weights for piston gages,** H. E. Almer, *Natl. Bur. Stand. (U.S.), Tech. Note 577,* 49 pages (May 1971).

[5] **On uncertainty in mass measurement,** J. R. Donaldson, *Natl. Bur. Stand. (U.S.), NBSIR 73-151,* 10 pages (Mar. 1973).

[6] **Weight cleaning procedures,** H. E. Almer, *Natl. Bur. Stand. (U.S.), NBSIR 74-443,* 7 pages (Nov. 1973).

[7] **Mass and mass values,** P. E. Pontius, *Natl. Bur. Stand. (U.S.), Monogr. 133,* 39 pages (Jan. 1974).

[8] **Notes on the fundamentals of measurement and measurement as a production process,** P. E. Pontius, *Natl. Bur. Stand. (U.S.), NBSIR 74-545,* 65 pages (Sept. 1974).

[9] **The use of the method of least squares in calibration,** J. M. Cameron, *Natl. Bur. Stand. (U.S.), NBSIR 74-587,* 30 pages (1974).

[10] **Surveillance test procedures,** H. W. Almer, *Natl. Bur. Stand. (U.S.), NBSIR 76-999,* 73 pages (Feb. 1976).

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B. Force

A force measuring system consists of two elements, an elastic device and a means to sense the distortion, or deflection, of that device under the action of applied forces. The calibration procedure consists of applying known forces, either tension or compression, to the elastic device and recording the sensed deformation. An analysis of the data provides correspondence between the system indication and the magnitude of the applied force. In some cases, force can be applied to two or more systems in series or series parallel arrangements using a hydraulic press. In this case, the correspondence for one system is established relative to the known correspondence for one or more previously calibrated systems.

Tension or compression calibrations in the range of 10 lbf to 10^6 lbf are performed in deadweight machines. Compression calibrations in the range of 10^6 lbf to 12×10^6 lbf are performed in a universal testing machine. In the latter case, the system being calibrated is loaded in series with one or more load cells that have previously been calibrated in a deadweight machine.

Subject to the conditions that the instruments submitted are sufficiently stable as to warrant the calibration effort, and that an adequate calibration service is not available elsewhere, NBS will perform the following tests:

(1) Characterize a force measurement device or system for the correspondence between indication and applied force.

(2) Perform calibration tests as specified by accepted voluntary standards or by companies or individuals. Test data will be processed in the manner specified or requested. Reports, however, may include a disclaimer with regard to the validity of the uncertainty estimate.

(3) On a time available basis, NBS will conduct tests to support developmental work on force measurement devices and systems. Devices must be proof tested and test procedures must be reviewed prior to submission of the device. Resulting test data will be returned in a letter report, normally without further analysis. Where intermediate parties are involved, the reports will be issued to the ultimate user. NBS will, when appropriate, discuss the calibration details with the user and reserves the right to modify the testing procedures accordingly. All work is done on an "At Cost" basis.

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[9] **Force sensor-machine interaction,** R. A. Mitchell and P. E. Pontius, *Proceedings of the 27th International Instrumentation Symposium (ISA), Indianapolis, IN, Instrumentation in the Aerospace Industry* **27,** 225-232 (1981).
[10] **Inherent problems in force measurement,** P. E. Pontius and R. A. Mitchell, *Exper. Mech.* **22,** No. 3 (Mar. 1982).

C. Vibration Measurements

Calibrations of vibration exciters and accelerometers are performed by comparison with the response characteristics of NBS standard vibration exciters or NBS standard pickups, or by absolute displacement measurements obtained with interferometric techniques. Details of these procedures are given in the cited references. Calibration results are stated in tabular form with the pickup sensitivity given in terms of either charge or voltage per "g" as a function of frequency. The customer may select a frequency range for calibration suitable to his needs from those listed in the current edition of the "Appendix—Fees for Services." Phase angles may also be determined upon request. Each piezoelectric acceleration pickup submitted for calibration which is used with a cathode-follower or amplifier shall be accompanied by the cathode-follower or amplifier and all necessary connecting cables. When instruments submitted are found to be unsuitable for test or are unreliable, a charge will be made to cover the cost of the work done.

References

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[15] **A real-time active vibration controller,** M. R. Serbyn and W. B. Penzes, *27th Int. Instrumentation Symposium, May 1981, Indianapolis, IN,* 489-494 (1981).

D. Acoustics

NBS performs calibrations of special microphones as described below.

Pressure calibrations are performed on type-L microphones satisfying the requirements of American National Standard S1.12.1967 (R1977), Specifications for Laboratory Standard Microphones. In addition, microphones must be suitable for use with the calibrating couplers shown in figures 6 and 10 of American National Standard S1.10-1966 (R1976), Method for the Calibration of Microphones. Copies of these standards can be purchased from the American National Standards Institute at 1430 Broadway, New York, NY 10018.

Pressure calibrations are reported in terms of open-circuit voltage per unit sound pressure applied uniformly to the diaphragm. The open-circuit voltage at the electrical terminals of a microphone may be influenced by stray capacitances evident at these terminals. These capacitances are defined by the geometrical configuration of the ground shield shown in figures 6 and 13 of S1.10 (R1976). If the ground shield dimensions are not adhered to in making use of the response levels reported by the Bureau, errors may result. Methods for the measurement of open-circuit voltage are described in Clause 2.1 and in figures 1 and 7 of S1.10 (R1976).

The free-field response levels of Western Electric Company Type 640AA condenser microphones, or equivalent, can be computed with good accuracy from the pressure response levels reported by the Bureau, using table A1 of S1.10 (R1976), provided the microphone is mounted on a preamplifier of size and shape illustrated in figure 12 of S1.10 (R1976). However, the use of manufacturers' response levels in conjunction with table A1 might result in errors unless the manufacturer has measured pressure response levels in accordance with S1.10 (R1976).

Since American National Standards Institute publications S1.10-1966 (R1976) and S1.12-1967 (R1977) were issued, certain types of "half-inch" diameter precision microphones have attained widespread use. Therefore, NBS has developed procedures for determining the pressure and free-field response of "half-inch" microphones. Since no current standards are directly applicable, details of the ground-shield configuration, coupler and other procedures will be incorporated in the test report.

Associated preamplifiers or power supplies should not be forwarded to the Bureau. The response levels reported are based on measurements of open-circuit voltage and are essentially independent of the electronic equipment used in the test, provided that the specified ground shield dimensions are used.

References

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E. Ultrasonics

NBS performs calibrations of ultrasonic transducers and reference blocks as described below.

1. Ultrasonic Transducer and System Calibration

Measurement services are offered for the determination of total forward radiated ultrasonic power into a water load for transducers as an element by themselves and for ultrasonic systems. These transducers and systems are ordinarily of the type used for nondestructive testing or for medical therapeutic or diagnostic purposes. There are some limitations on aperture size.

Transducers are generally measured using a modulated radiation pressure system which gives output power versus frequency over any part of a frequency range of about 1-20 MHz. Absolute power is also measured at specific frequencies to yield the transducer's radiation conductance for continuous-wave excitation. Power levels from a fraction of a milliwatt to cavitation in water can be accommodated.

Ultrasonic system time-averaged total power into a water load is measured using a calorimeter. The power levels can be from a few milliwatts to cavitation in water and frequencies from about 1-15 MHz. The systems can be either continuous-wave or pulsed type since the system responds to a time average of the total power.

Some air-backed quartz transducers are also available on a loan-for-fee basis. These transducers have accurately known total power output if the applied cw voltage input is known. They are used in providing a known source for the in-situ calibration of ultrasonic power measurement systems.

References

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2. Acoustic Emission Sensors

Acoustic emission sensors are used as part of systems to passively determine or monitor the integrity of structures. The method relies on the detection of stress waves in a structure due to local changes associated with a defect. The sensors are generally used in the frequency range of from 0.1 to 1 MHz. Such sensors can presently be calibrated at NBS to obtain the amplitude and phase spectra using the surface wave technique. A point-force step function is created as an input to a large polished steel block. A standard transducer and a transducer under test are located on the same surface of the block as the input. The output waveforms of these transducers are processed to determine the absolute response of the transducer under test over the approximate range of 0.1 to 1 MHz. If the transducer under test is to be used as a transfer device, it must have adequate sensitivity over the frequency range of interest.

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Breckenridge, *Matls. Eval.* **39,** No. 1, 60-68 (Jan. 1981).
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3. ASTM-Type Ultrasonic Reference Blocks

The ultrasonic response of 7075 aluminum alloy reference blocks is determined relative to an NBS interim reference standard by immersion, pulse echo, longitudinal wave testing. An NBS developed procedure is used. The data are also compared to the data base of all blocks measured by NBS.

Response following the ASTM Recommended Practice E-127-80 can also be determined. The response of steel reference blocks can also be obtained by special arrangement.

References

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F. Fluid Flow

Standards for flow measurement of fluids are maintained using water, air and a stable hydrocarbon as test mediums. These facilities are used for extending the types of measurement services, for research on how to characterize flow measurement systems and to evaluate and test transfer flow standards.

1. Fluid Quantity and Flowrate Meters

Flow meter systems, i.e., meter, pertinent adjacent tubing, and readout equipment having demonstrated temporal stability and precision commensurate with the quality of the calibration are accepted for calibration over a wide range of flows in air, water, and hydrocarbon fluids. Meter systems should not be sent to the Bureau until all arrangements for the calibration have been completed. Specifically, a purchase order for the cost of the calibration should be included with the item or sent under separate cover when the meter assembly is shipped. If, when submitted, meter systems are found to be unreliable or unsuitable, a calibration may be discontinued and a charge will be made to cover the cost of the work done.

Meter systems submitted should have connections for A/N flare fittings up to 2-in (5 cm) nominal diameters, or with connections for National Pipe Thread fittings up to 3-in (7.6 cm) nominal diameter and larger meters must terminate with ASA 150-lb steel flanges, or grooved-end steel pipe compatible with Victaulic couplings (for water meters), or with adapters thereto; for air, flanges must terminate with ASA 300-lb steel flanges except for laminar element flowmeters operated near ambient pressure levels. Connections other than these should not be submitted unless special arrangements have been made in advance.

Fees are based on the actual cost of calibration.

Meters must be submitted with connections for A/N flange fittings up to 3-in nominal diameters, or with connections for National Pipe Thread fittings up to 3-in nominal diameter. For

pipe sizes 4-in nominal diameter and larger, meters must terminate with ASA 150-lb steel flanges, or grooved-end steel pipe compatible with Victaulic couplings (for water meters), or with adapters thereto. Meters with connections other than these should not be submitted unless special arrangements have been made in advance.

References

[1] **Introduction to liquid flow metering and calibration of liquid flowmeters,** L. O. Olsen, *Natl. Bur. Stand. (U.S.), Tech. Note 831,* 60 pages (June 1974).

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G. Aerodynamics

Calibrations of air speed measuring instruments are performed in two high quality wind tunnels covering the speed range 4–4000 meters per minute (0.1–150 mph) using a laser velocimeter and a laboratory standard Pitot-static tube as the primary velocity standards for the lower and higher speed ranges, respectively. The low velocity wind tunnel, which uses a laser velocimeter standard, covers a speed range of 4–540 meters per minute and has a test section area of 0.9 m by 0.9 m. The second wind tunnel has two test sections. The first of these has an area of 1.5 m by 2.1 m with a speed range of 2–46 m/sec. The second test section has an area of 1.2 m by 1.5 m with a speed range of 4–82 m/sec.

The NBS air flow facilities, apart from providing a calibration capability for air speed measuring instruments, are extensively used for fundamental research on turbulence and fluid dynamical problems of national interest that serve to extend flow and fluid measurement competence.

References

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[2] **Low velocity performance of a ball bearing vane anemometer,** L. P. Purtell, *NBSIR 78-1485,* 19 pages (June 1978). Order from NTIS.

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[4] **A low-velocity airflow calibration and research facility,** L. P. Purtell and P. S. Klebanoff, *Natl. Bur. Stand. (U.S.), Tech. Note 989,* 18 pages (Mar. 1979). Order from NTIS. Also available from Supt. of Documents, Washington, DC, SD Stock No. SN003-003-02038-9.

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CHAPTER IV

IV. Electrical Measurements—DC and Low Frequency

The National Bureau of Standards has the responsibility for the establishment and maintenance of the legal electrical units and, in addition, for making them available for use by industry, science, and government at all levels. This chapter describes the dissemination of the electrical units and related electrical and magnetic quantities in the frequency range from 0 (dc) to 1 MHz. Dissemination takes place in three ways: via routine calibration of electrical, electronic, and standards and measurement apparatus of the highest accuracy; by in-situ calibrations performed on equipment which for technical reasons cannot be moved to or calibrated at NBS; and through Measurement Assurance Programs. Educational, consultative, and metrology engineering services are also available. The following sections contain more detailed descriptions of each type of service.

The group of services offered has evolved over the years in response to needs emanating from the measurement, technical, and scientific communities. Suggestions of new, needed or useful, services are welcomed by NBS.

Note: Calibration and other metrology-related services to support measurements of electromagnetic quantities in the frequencies above 1 MHz are discussed in the next chapter.

Services

Educational: Seminars and workshops covering selected specific topics in the field of electrical metrology are organized and held from time to time. Examples of areas covered in recent and planned seminars include power and energy measurements, measurements in pulse power systems, and voltage MAP techniques. These are advertised in the Appendix to this publication.

Consultations: Arrangements may be made for consultations with appropriate NBS staff members either at NBS or in a client laboratory to solve critical measurement problems. This is done on a cost-reimbursable basis. Because of the depth and variety of NBS staff expertise, many such problems may be solved with a telephone call. Requests for limited assistance, such as can be handled with a telephone conversation or a letter, are encouraged as they contribute to NBS awareness of problems facing the metrology community.

Research and Development: R&D activities on new methods of measuring electrical quantities and the development, design, and construction of measurement apparatus are natural outgrowths of the Bureau's unique responsibility. The competence of specialists in electrical measurements is reinforced by the ready accessibility of experts in the many other technical areas of NBS. Expertise from diverse fields, such as cryogenics, solid state electronics, semiconductor physics, automatic data processing, and metallurgy may be brought to bear on a problem. Special measurement problems of concern to industrial or technical organizations, whether they arise in the course of research or result from application of new technology, may be addressed by NBS scientists and engineers on a contractual basis.

Publications: NBS publishes the results of its researches extensively to aid others who may wish to use its developments or services. Up-to-date lists of publications (NBS LP 38 and LP 94) on electrical units, instruments, and measurements are available upon request. NBS is a member of GIDEP, the Government-Industry Data Exchange Program. All NBS publications will be included in the GIDEP data bank for ready reference.

Calibrations: Routine calibrations of standards and precision electrical measurement apparatus submitted to NBS are performed on a cost-reimbursable basis using permanent facilities at the Bureau. These services are intended to support primary standards laboratories and the development of state-of-the-art measurement instrumentation. Accordingly, NBS will calibrate only standards and apparatus of the highest quality except under unusual circumstances such as to

fulfill legal requirements or to resolve certain technical disputes. Those requiring support for secondary standards are encouraged to seek help from the numerous commercial calibration sources available. NBS can be of some assistance in locating a convenient source.

NBS will, within the constraint of its resources, address critical measurement problems not explicity covered in the fee schedule. Involvement in these problems may be negotiated in certain measurement areas as indicated in the Appendix (Fee Schedule) to this document by the heading "Special Measurement Services by Prearrangement."

Note: NBS does not generally provide tests for electrical devices or supplies not directly related to the field of measurement. Tests are not generally performed on low-accuracy electrical devices or components not intended for use as reference standards.

Limited manpower precludes NBS from undertaking repair activities. Therefore, all apparatus submitted for calibration should be free of defects and in proper working order. Electrical contacting surfaces should be in proper condition both mechanically and electrically. Minor repairs and necessary cleaning may be performed, workload permitting, at the discretion of NBS personnel and on an at-cost basis. Electrical standards and instruments, with the exception of unshippable saturated standards cells, may generally be shipped. However, due to their delicate nature and to the limited NBS repair capability, it is advisable to pack them extremely carefully. Special reusable shipping containers customized for this purpose are a worthwhile consideration.

A report is issued upon the calibration of each item. This report contains the measured values of each of the appropriate attributes of the device and their uncertainties. The measured values and the reported uncertainties describe the results of the calibration process only. No allowance is made for the long-term drift of the item, for its performance under conditions differing from those of the test, or for the effects of transporting the item to and from the Bureau. Uncertainties associated with these effects must be quantified by the user from additional measurements. NBS personnel can advise in setting up the appropriate experiments.

NBS neither insists upon nor recommends intervals between NBS calibrations for electrical standards except as explicitly stated in the following sections. These intervals depend upon the performance of the individual standard and the accuracy requirements of its application. These must both be determined by the user. A number of users make lists of intervals they have determined to be necessary for specific items available to anyone interested. NBS can serve as a focal point for contacting those organizations.

Laboratory turnaround time for fixed-fee calibrations is typically 6 weeks, depending upon workload, except in the case of standard cells, which require longer periods to stabilize. An estimate of turnaround time will be given for at-cost items.

Technical details particular to each type of calibration are to be found in the following appropriate sections of this chapter.

In situ Calibration: NBS performs in situ calibrations in instances in which the transportation of the apparatus to be calibrated to the Bureau is not possible or when the magnitude of the stimuli required lies outside its in-house capability. For example, NBS has developed a special portable, current-comparator bridge of high accuracy. This bridge, together with low- and intermediate-voltage, compressed-gas-dielectric capacitors, can readily be taken to field sites or high-voltage laboratories. This system is then used by NBS personnel to calibrate voltage transformers, high-voltage capacitors, shunt reactors, and other high-voltage equipment for the power industry. This approach not only permits equipment to be calibrated in its normal environment and location under normal conditions of use but serves as well as a training experience for the calibration customer's personnel.

Well-established Measurement Assurance Programs (MAP's) are available in the areas of resistance, capacitance, voltage, and electrical energy. Specifics of each of these are discussed in the appropriate following technical section.

Consideration will be given to establishing new Measurement Assurance Programs, in areas other than those described below, where needs can be documented. For those instances where the required program is not generally applicable to a broad user group, NBS may provide the requesting organization with guidance so that they may develop the necessary techniques themselves.

The most recent information on dc- and low-frequency electrical measurements is frequently published in:

"IEEE Transactions on Instrumentation and Measurement" [December issues are proceedings on

the Conference on Precision Electromagnetic Measurements (CPEM) and Electrical and Electronic Measurement and Test Equipment Conference (EEMTIC) alternately].

IEEE
345 East 47 Street
New York, NY 10017

"Metrologia"

Springer-Verlag New York, Inc.
175 Fifth Avenue
New York, NY 10010

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A. Resistance Measurements

Services covered in this section include the following types: Resistance Measurement Assurance Programs, resistance standards with nominal values in the range between 10^{-4} and 10^{6} Ω, high-valued standards falling in the range between 10^{6} and 10^{14} Ω, and standard resistors for the measurement of high currents. Resistors not intended for use as primary standards, such as common decade resistance boxes, are not normally dealt with.

In addition to the routinely offered resistance measurement services described here and in the Appendix to this document, NBS will provide such other special services as to aid in the solution of particular measurement problems deemed to be significant. For example, the Bureau has provided a special-valued resistor which, when used at a production line, assisted a company in ensuring the quality of high precision manufactured electronic components. Requests for assistance of this type will be given thorough consideration. If undertaken as a development project, programs of this nature will generally lead to joint publications in the open literature describing the new measurement techniques or approach. Such services are provided on the basis of operational costs being defrayed by the user.

1. Resistance MAP Services

In the Resistance Measurement Assurance Program, the quality of the client's laboratory standards, maintenance program, and ability to disseminate the unit of resistance is assessed and new values determined for his standards, if necessary. This is done by viewing the measurement process as a system and sampling the measurement quality at a point in that system using NBS transportable standards with well understood properties. As the objective is to determine the laboratory's primary capability, NBS standard resistors at levels selected by the client are measured as unknowns in the client's standards laboratory or elsewhere as appropriate. In addition to using their normal procedure to obtain assignments for the values of the transport group, the laboratory uses NBS suggested procedures which permit determination of the process precision as well as offsets in equipment, etc. Data taken using the client's normal measurement process are combined with those taken before and after the transport process at NBS using least squares techniques to determine the precision and random error of the measurement process as well as the offset of the calibrated values from those expected.

It should be understood that participation in this program is generally not advisable unless one is required to support resistance measurements at or near the state-of-the-art in accuracy and is willing to adopt a system for the continuous surveillance of standards during the intervals between NBS MAP transfers. A successful transfer requires a considerable amount of data collection and a willingness to become involved in the data analysis process. Data supplied in the course of routine NBS calibrations suffice for normal measurement requirements of standards laboratories if proper

methods are used by the laboratory to quantify the additional uncertainties caused by transportation and their own measurement process. NBS stands ready to assist client laboratories in this regard.

Apparatus and procedures exist for routine performance of this service at the following levels of resistance, listed in order of increasing uncertainty: 1, 10^2, 10^3, 10^4, 10^7, 10^8, 10^9, and 10^{10} Ω. Although the actual uncertainty of these transfers depend upon the capability of the laboratory, they can be said to range from sub-tenths of a ppm in the case of the 1-Ω level to the 20-30 ppm range for the highest valued resistors. Measurement assurance programs to address the maintenance problem at other levels of resistance may also be arranged by consultation.

2. Resistance Standards (10^{-4}-10^6 Ω)

Resistance standards with nominal values in the range between 10^{-4} and 10^6 Ω are calibrated by comparison with NBS working standards of the same nominal value. This service is for primary standards of resistance only. Because of this, and to maximize their value as standards, resistors submitted for calibration should have the following attributes:

1. A drift rate of less than 20 ppm per year
2. A temperature coefficient of less than 30 ppm per °K at the temperature of use
3. A low thermoelectric coefficient against copper, especially for low-valued resistors

In essence, the standard should be capable of performance at the 0.2 ppm level over a short period (1-3 days).

The standard resistors are generally calibrated in stirred oil at 25 °C. Normally a power level of 0.01 Ω is maintained in the resistor during the calibration as at that level neither the load coefficient of the standard nor the flow characteristics of the oil bath have appreciable effect upon the outcome of the calibration. At the levels of accuracy involved, four terminal measurements are required for resistors whose nominal value is 100 Ω or less. Any resistor submitted should be designed accordingly. Precision standard resistors of this type are commonly designed with amalgamated current terminals. These should be clean and in generally good condition upon submission to NBS for test.

High-quality resistors suitable for use as standards, but not intended for oil immersion, may be accepted for calibration in air (22-44 °C) if their variation of resistance with temperature does not exceed 2.5 ppm per K and if the design provides for accurate determination of the temperature of the resistor under conditions of test. Such standards may have any nominal value. The uncertainty of calibration depends largely upon the performance characteristics of the resistor itself. Acceptance for NBS calibration of these standards is at the discretion of the Bureau.

A number of services may be performed by prearrangement as indicated in the Appendix to this document. They are:

a. The determination of pressure coefficients for Thomas-type resistors and others affected by variations in ambient pressure
b. The calibration of resistance standards at power levels exceeding 0.01 W
c. The determination of the load (power) coefficients of standard resistors for nominal values of one ohm and higher

3. Resistance Standards (10^7-10^{12} Ω)

High-valued resistance standards in the range between 10^7 and 10^{12} Ω are calibrated at room temperature (22-24 °C) and at a relative humidity of less than 50 percent. This is done by one-to-one comparison with NBS standards at levels of 10^{10} Ω and lower and via capacitive discharge techniques for those resistors whose nominal value exceeds 10^{10} Ω. Uncertainties depend upon the stability and performance of the specific resistor involved. They can be as low as 10-20 ppm for 10^7 Ω resistors to as high as 0.3 percent for 10^{12} Ω.

Because of the high resistances of these standards, their measured values can be affected by leakage currents, which in turn are related to relative humidity and surface cleanliness. Accordingly, they should be so constructed and treated that the effect of humidity is minimized. As with other standards, these resistors should be made of suitable materials and processed in such a manner that resistance values do not change appreciably with time relative to the uncertainty required by their use. The resistance of such standards is frequently highly voltage-dependent. Hence, the magnitude of the appropriate test voltage should be specified for each resistor

submitted. Each resistor should also have an identifying number engraved on or permanently attached to it.

The Bureau does not have facilities for the determination of temperature or humidity coefficients of resistors whose nominal values exceed 10^6 Ω. Allowance for normal variations due to these effects is made in the uncertainty statement of the test.

4. Resistance Standards (High Current)

Standard resistors for use in precise measurement of high direct currents (shunts) are also calibrated by NBS. Normally only those resistors of 0.04 percent accuracy or better are calibrated. Although the uncertainty of measurement, as in other areas, depends largely upon the performance of the standard involved, it may be generally said that oil-immersed shunts having a rated current capacity of 50 A or less can be calibrated with uncertainties of the order of 50 ppm as can those designed for use in air at currents of 25 A or less. As current ratings increase, calibration uncertainties increase.

To be effective, standard resistors for current measurements must be of four-terminal design, i.e., one for which the resistance is defined as the ratio of the open-circuit potential difference between the potential terminals to the current flowing through the current terminals. The resistance value will be definite and reproducible only if the current flow pattern at the potential terminals is independent of the way in which current is introduced at the current terminals, and if the voltage observed at the potential terminals is independent of the location of leads on the potential terminals. In some instances where this has not been done, the type and location of connections to the current terminals can be specified adequately to fix the flow pattern at the potential terminals.

Resistors for very high currents (above about 1000 A) require considerable power so that their temperature rise between low and rated current, and the resulting change in resistance, will depend not only on their design, including means provided for dissipating heat, but also on the connecting bus bars and their junctions to the resistor. Bus bars of generous cross-section may carry away a significant part of the heat generated in the resistor. In addition, contact resistance at the points of connection to the bus bars, unless carefully minimized, may contribute appreciably to the heating. (Contact resistance of bolted connections depends on area of contact, cleaniness of surfaces, and pressure.) Resistance determinations made in the laboratory at rated current, therefore, may be of little value because the working temperature conditions cannot be duplicated. The best experimental procedure to use in such cases is to place the standard in a temperature-controlled enclosure and measure its resistance with a comparatively low test current when it is heated uniformly to a temperature approximately that at which it will operate in service. From data at two or more elevated temperatures, combined with that at room temperature, a curve can be plotted from which the resistance at the operating temperature can be read, provided this temperature is determined by the user with the resistor under the actual operating conditions.

Changes in resistance may also result from strains in the resistance element produced by mechanical forces incidental to clamping the resistor connections, as well as from inherent internal expansion constraints on resistor parts, or forces from the magnetic field produced by the current.

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B. Precision Apparatus

Ratio, transfer, and scaling devices of high accuracy are covered in this category. Included are Hamon and other transfer devices, and inductive voltage dividers. Specific details for each type of calibration not following or contained in the Appendix to this document may be obtained from the office designated in the Appendix.

In general, precision apparatus should be packed carefully to avoid damage during shipment. Instrument lids of light metal or wood associated with heavy items of equipment should be protected from damage by the weight of the instrument itself such as might occur if the shipping container were inverted during transportation.

Calibrations of such apparatus are carried out at room temperature (22-24 °C) with the exception of Hamon transfer units designed for oil immersion at 25 °C. These devices exhibit a certain amount of after effect due to the abrupt change in the temperature of resistors. Accordingly, they are allowed to "soak" for a period not shorter than 1 week at their normal operating temperature before calibration. This same precaution should be observed in use.

Inductive Voltage Dividers

Inductive voltage dividers (decade transformer dividers) are accepted for calibration only at frequencies near optimum design frequencies. The largest contribution of instability in inductive voltage dividers often arises in the decade switches. Variable contact resistance in these switches sometimes affects the stability of voltage-ratio measurements to a significant extent but is most evident by its effect on the phase angle. When a decade inductive voltage divider exhibits large changes in phase angle for repeated measurements after the switches have been disturbed, the divider should no longer be considered satisfactory for use as a reference standard of voltage ratio. Inductive voltage dividers which use pushbutton switching or which incorporate a resistive divider as a fine adjustment usually are not accepted for calibration.

Corrections to the separate decades of an inductive divider, in general, cannot be simply combined; however, the correction to a step setting of one of the higher decades usually is independent of the setting of the lower decades. The effects of stray impedances must be corrected by connecting the case to the divider at one point, and unless otherwise specified, the case will be connected to one of the common terminals.

Decade inductive voltage dividers are calibrated at the Bureau by a comparison method, using as a working standard a well-constructed inductive divider which has been calibrated previously by capacitance-ratio or other suitable methods. The comparison method is simple and convenient and can be used in other laboratories for the rapid calibration of other voltage dividers. Also, it can be extended readily to permit calibration of the lower decades of a divider in the user's laboratory. (See *NBS Technical News Bulletin* **49**, 1, Jan. 1966.) Accordingly, it is recommended that, in general, only one divider from a laboratory be submitted to the Bureau for calibration and that other reference dividers be calibrated by a comparison method using it as a standard.

C. Impedance Measurements

1. Impedance MAP Services

The Measurement Assurance Program in capacitance is routinely carried out at the 1000 pF level. An NBS designed transportable capacitance standard forms the basis for this service. It consists of four specially-selected commercial gas dielectric 1000 pF capacitors housed in a temperature-controlled oven capable of sustained operation via a battery pack. Data handling in general is similar to other MAP's. Redundant measurement designs provide data for estimation of process precision and of the magnitude of some systematic effects such as ground loops. Before and after data are combined with client data in a linear regression analysis used to determine the difference between the client's unit of capacitance and the legal unit. Upon completion of a number of transfers, this difference may be characterized as a function of time and that characterization used in conjunction with the results of a continuing internal surveillance program to ensure the quality of capacitance measurements at the client facility. The uncertainty of the

process depends very much on the client's laboratory capability and could be as low as one in 10^7.

Similar programs at other levels of capacitance will be initiated as needs and resources dictate. NBS personnel can assist in the design of measurement assurance programs using client equipment and normal routine calibration data if circumstances permit.

2. Standard Capacitors

The following apply to the calibration of standard capacitors at NBS:

(a) Calibrations are ordinarily performed at an ambient temperature of 23 ± 1 °C except for high stability gas dielectric capacitors. These are placed in a highly insulated chamber for 48 hrs. to achieve temperature stability during calibration. Calibration temperature is reported to within ± 0.1 °C. Relative humidity is maintained at 50 percent or less in all cases.

(b) Precision three terminal air capacitors, such as ESI Model SC1000 and GENRAD Model 1404 have been found to be variously affected by mechanical shock. Accordingly, two types of calibrations are offered. The higher accuracy calibration requires a qualification test to determine the effects on capacitance of various impacts and changes in orientation. Results of this test are coupled with the random error of the precision calibration which follows to provide a definitive accuracy for the process. For the lower accuracy test, a similar calibration, albeit with reduced resolution, is performed. The assigned uncertainty is fixed and has been deduced from an analysis of data taken from tests on a large population of standard capacitors.

(c) The frequencies available for these calibrations depends upon the type of capacitor and its connectors. In general, capacitors with coaxial connectors can be calibrated at 100, 400, and 1000 Hz. Capacitors with binding posts, banana plugs, etc., can be calibrated at 66-2/3, 100, 400, 1000 and 10,000 Hz.

(d) The capacitance value given is the equivalent parallel capacitance. In general, a determination of the equivalent parallel conductance with high accuracy is not feasible; however, for solid dielectric capacitors an approximate value is given without charge.

(e) The uncertainty stated in the report of calibration is determined in part by the accuracy of the Bureau's measurements and in part by the characteristics of the capacitor itself, and is sufficiently broad to allow for variations in the stray capacitance at the connectors, variations in temperature of a few degrees Celsius, considerable variation in relative humidity and atmospheric pressure, and frequency deviations of a few percent from the stated test conditions. Over the above frequency range, and in the capacitance range from 0.001 to 100 μF, the uncertainty usually lies in the range 0.002 to 0.5 percent.

(f) When capacitors requiring terminal plugs (banana plugs) for parallel connection are sent to the Bureau, the plugs which will be used with the capacitor after calibration should be sent also. If such a capacitor arrives without plugs, the Bureau must attach plugs temporarily in order to calibrate the capacitor. The plugs used by the Bureau are GENRAD Type 274-P. If after calibration with these plugs, the capacitor is used with plugs of even slightly different length and base, the value of capacitance can differ significantly from the value reported. Unless otherwise requested, the measured value reported by NBS is the capacitance added when the standard is plugged directly into the binding posts of the Bureau's bridge. For two-terminal GENRAD capacitors Type 1401, Type 509, and Type 1409 (used as two-terminal capacitors) it has been found that plugs which are different from the Type 274-P can cause a capacitance increase ranging from 0.04 to 0.14 pF. For three-terminal use of GENRAD Type 1409 capacitors it has been found that different plugs can cause a capacitance increase ranging from 0.01 to 0.04 pF. No significant change in conductance has been found in either the two-terminal or three-terminal value. The importance of terminal connection methods becomes extremely critical when capacitance values of 0.01 μF or less are being measured. Improved accuracy in two-terminal measurement can be realized if standards are provided with precision coaxial connectors.

(g) In the case of direct capacitance standards, it is assumed that the connectors are coaxial. While the connectors available for this purpose are adequate, it should be noted that changes or instabilities in the impedance of the shield or guard connection of a three-terminal capacitor can change the capacitance significantly.

(h) The following capacitors are no longer accepted for calibration by the Bureau:

Two-terminal air capacitors with exposed terminals, nominal value of capacitance 1000 pF or less. (For example, GENRAD Type 1401 capacitors with either old or new style terminals.) Two-terminal air capacitors with the "low" terminal (ground terminal) extended and surrounding

the "high" terminal are acceptable. Refer questions regarding acceptable types to the information source given in the Appendix.

(i) In applying the fee schedule in the Appendix to decade capacitance boxes and variable air capacitors, the first entry applies to a determination of the zero capacitance and conductance of the box (all dials set at zero). The second entry applies to the determination of the capacitance and conductance added to the circuit when any one dial is advanced from zero to a specified setting, and at the frequency used in determining zero capacitance. For measurements at additional frequencies the schedule is applied in the same manner, i.e., the higher fee is used for the first point (zero calibration) at the new frequency and the lower fee applied to additional points at that frequency.

(j) Unless otherwise specified in the client's purchase order, capacitors with solid dielectric will be calibrated as two-terminal capacitors (measurement of "grounded" capacitance, case connected to low terminal).

(k) If a capacitor arrives in a condition such that minor repairs are required, the owner will be notified and requested to supply a letter granting permission for NBS to perform the repairs.

3. Standard Inductors

Standard inductors for use in ac bridges are tested at 100, 400, 1000, or 10,000 Hz at a room temperature of 23 °C and a relative humidity of 50 percent or less. Measurements at 10,000 Hz are limited to standard inductors of 0.1 H or less. Most inductors used at 60 Hz can be tested at 100 Hz since the variation of inductance with frequency in this range is usually negligible. Purchase orders should state which frequency or frequencies are to be used for calibration purposes. If no test frequency is specified in the order, measurements will be made at 1000 Hz. A metal encased standard is calibrated with the case connected to the "low" terminal of the inductor unless other conditions are specified. Variable inductors used as circuit elements in laboratory setups are low accuracy devices which do not come within the purview of this schedule and should not be submitted for calibration. Q values are not supplied for inductors calibrated in this section. Inductors intended for use as Q standards at radio frequencies are covered in the next chapter.

Accuracy: The effective series inductance value is given to as many significant figures as are justified at the time of measurement. The uncertainty figure given in the report of calibration will vary from 0.02 to 0.2 percent depending on the nominal value of the inductor and the frequency of the test current employed.

Usually inductors can be shipped safely by express but they should be packed carefully to avoid damage to the coil fastenings and terminals.

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D. Voltage Measurements

1. Voltage MAP Services

The Volt Transfer Program, VTP (the MAP for standard cells), is designed to reduce the uncertainty of the assignment of the unit of voltage at the participating laboratory, and to provide the laboratory with quantitative information about its own measuring process.

In the VTP, rather than have standard cells sent to NBS for calibration as is usually done, the Bureau will provide transport standards of voltage, appropriate measuring techniques, and overall supervision of the experiment. As far as is practical, the service will be tailored to meet the needs of each participating laboratory.

The experiment is carried out in three phases: First, NBS analyzes the participant's procedures and measurement setup. From the analysis, NBS proposes certain internal experiments, determines various operating parameters, and establishes that the local measurement process is in control. Where measurement problems are encountered, NBS will assist in solving these problems even to the extent of sending personnel to the laboratory, if necessary.

Second, NBS provides the laboratory with a suitable transport standard (saturated cell group) and the procedures for intercomparing it with its reference group of standard cells. Usually, the transport standard will be shipped via air freight under carefully controlled conditions.

Finally, upon return of the transport standard, NBS analyzes the results and suggests any change in the laboratory's unit of voltage that might be in order.

The level of participation by each laboratory will depend on its own internal requirements. It may vary from four such experiments per year to one every 2 years. This type of approach eliminates several sources of uncertainty that are inherent in the regular procedure in which customers send or bring their cells to NBS. This is because the Volt Transfer Program calibrates the whole process and not just a portion of it. At the present time, NBS is quoting as the standard deviation of a single experiment 0.14 ppm or a three standard deviation uncertainty for the complete calibration of 0.42 ppm. It should be again emphasized, however, that this service is not meant to replace the regular calibration procedure. Rather, it is designed for those laboratories that need and can utilize the most precise unit of voltage obtainable.

To keep the data analysis activity at a manageable level, the transport standard should be compared with a single laboratory reference group of cells containing a number of cells such that a single measurement design may be used for a total comparison. The use of cells configured so as to require more than a single, statistically optimized measurement design to assign values to the transport standard in terms of the client's unit of voltage will result in extra charges. Large designs, i.e., those involving more than 12 cells, are undesirable as individual cell drifts can tend to mask the estimates of process precision levels. NBS can provide computer programs and design information to permit the client to perform his own data analysis where large numbers of cells are involved.

Since the amount of equipment available for this program is limited, it is vital that interested parties advise us of their intent to use the program in any calendar year by the end of the previous year.

2. DC Voltage Standards

Routine calibrations of voltage standards involve the following considerations:

(a) Unsaturated cells require approximately 3 weeks for a complete calibration. Such cells are placed in a thermally lagged enclosure and their emfs are read daily for a period of 10 days. If the measured emf fluctuates unduly or is unusually low, or if the cell shows abnormal indications, the report of calibration will reflect these circumstances. Unsaturated cells are not likely to be injured by normal transportation (mail or express) if they are packed carefully. Because of the possible hazard from freezing, shipment during very cold weather should be avoided.

(b) Saturated standard cells of the unshippable type should always be transported by messenger because such cells should never be tipped from an upright position by more than 45° in any direction. Unshippable saturated cells contained in portable, temperature-regulated enclosures should also be transported by messenger and with the enclosure activated or under power, if possible.

(c) Saturated standard cells of the shippable type housed in portable thermoregulated enclosures should be packed carefully and shipped under power if possible. Liquid-in-glass thermometers normally mounted in such devices should be removed and provided with additional rigid packing for protection against breakage. Enclosures having a nominal cell temperature of 28 °C or lower should not be transported during the summer due to the danger of over heating. Enclosures should not be energized by using the ac power mains while they are packed in shipping containers.

(d) Saturated standard cells which arrive having been maintained continuously at their nominal temperature of use will, workload permitting, undergo test immediately upon receipt for a period not to exceed 4 weeks, unless other arrangements are made. If such cells perform abnormally with respect to the typical performance of like cells in similar environments, the owner will be notified. Arrangements for further testing may be made at that time if desired. Cells will be returned as soon as possible after calibration.

(e) Saturated cells arriving at a temperature other than their nominal temperature of use will be brought to their use temperature as soon as possible after receipt. Starting the month after they are initially brought to temperature, weekly readings will be taken to observe the stability of the cells. When the cells stabilize, 10 daily readings will be taken and used to assign values to them. This process will not exceed 90 days without special arrangements being made.

(f) Solid-state voltage reference devices for test must have output voltages in the range between 1.015 and 1.020 V and/or 10 V and a rated accuracy of 0.005 percent or better. Such devices will be tested under continuous power.

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[13] **A resistive voltage-ratio standard and measuring circuit,** R. F. Dziuba and B. L. Dunfee, *IEEE Trans. Instrum. Meas.* **IM-19,** No. 4, 266-277 (Nov. 1970).

E. Electrical Instruments (ac-dc)

RMS ac-dc transfer standards [thermal voltage converters (TVC's) and thermal current converters (TCC's), covering the ranges 2 Hz to 1 MHz, 1 mA to 20 A, and 0.5 to 1000 V] meeting certain requirements, are accepted for calibration. Accuracies and limitations are listed in the table at the end of this section.

(a) Ordinarily only ac-dc transfer standards and thermal converters of 0.05 percent rated accuracy or better are accepted for test, which consists of ac-dc difference determinations as described below.

(b) Ac-dc difference tests consist of determinations of the differences between the quantities (current, voltage, or power) required to give the same response (output) of the transfer standard on alternating current and on reversed direct current (the average of the two directions of direct current). The alternating quantity, Q_a, required for a given response of the instrument or converter is then $Q_a = Q_d(1+s)$ where Q_d is the average quantity required for this response on reversed direct current, as determined by dc standards, and s is the small fractional ac-dc difference.

(c) Tests are recommended at rated voltage or current on each range at 20 kHz (the upper limit for NBS' best accuracy) or at the highest frequency of interest. Additional tests are recommended at lower frequencies only if the ac-dc differences are large at the initial frequency. Since the need cannot be predicted, it is recommended that the purchase order include an allowance for a few such tests, perhaps by stating an upper limit of cost. A second test at 600 V is recommended for 1000 V ranges, for these ranges may be affected by self heating. Tests are made from 30 kHz to 100 MHz or more at NBS Boulder, CO (see ch. V).

(d) In addition to the high-frequency tests, an ac-dc difference test (ordinarily at 20 Hz) is recommended for one range, to verify the low-frequency accuracy. Thermoelements have a low-frequency limit, below which they fail to integrate properly. The ac-dc difference may approach 0.02 percent at frequencies ranging from about 5 Hz for most low-range thermoelements to about 60 Hz for some thermoelements with ratings above 1 A. This low-frequency ac-dc difference is the same for all ranges of a multirange converter in which a single thermoelement is used with shunts or multipliers. For convenience, usually a low-voltage or current range is chosen for the test.

(e) At special request, high-grade thermal voltage converters of the coaxial type, having plug-in series resistors for one or more thermoelements to form ranges from 1 to 1000 V, can be evaluated to 20 ppm at a higher cost. The dc reversal differences of the converter must be less than 200 ppm and the ac-dc differences less than 100 ppm. The design should permit intercomparisons between ranges by the user. If such intercomparisons are made, initial tests at NBS are recommended only for the lowest, middle, and highest ranges, to provide tie points and to verify the accuracy of the user's intercomparison (step-up) procedures. Any relative changes in the converters can be detected by subsequent periodic intercomparisons in the user's laboratories. If no changes are observed, retests at NBS should not be necessary.

(f) At special request, the ac-dc differences of high-grade thermal converters (thermoelements) for current measurements from 5 to 50 mA can be determined by direct comparison with the basic NBS ac-dc transfer standards, to 5 ppm from 20 Hz to 20 kHz and 10 ppm up to 50 kHz, at a higher cost. The dc reversal differences of the converters must be less than 100 ppm and the ac-dc differences less than 20 ppm.

(g) The ac-dc differences are small and very stable in well-designed, rigidly constructed ac-dc transfer standards. For such a standard, a recalibration interval of not less than 5 years is recommended if checks are made periodically by the user (by comparing it with another ac-dc transfer standard or by measuring a stable ac voltage standard with adjacent ranges of the transfer standard).

Range and uncertainties of ac-dc difference calibration

Frequency	2-5 Hz	5-20 Hz	20-Hz 20-kHz	20-50 kHz	50-100 kHz	0.1-0.5 MHz	0.5-1 MHz
Voltage limits (V)	50	100	1000	1000[1]	600	100	100
Current limits (A)	0.05	0.05	20	16[2]			
			Uncertainty (%)[3]				
Multi-range TVC's	0.02	0.01	0.005	0.01	0.01	0.02	0.03
Coax single range TVC's	.02	.01	.002[4]	.003[4]	.005[4]	.02	.03
TE (5 to 50 mA)	.02	.01	.0005[4]	.001[4]			
TCC (0.005 to 5 A)	.02	.01	.005	.01			
TCC (5 to 20 A)			.01	.01			

[1] 200 V at 20 Hz
[2] 5 A at 20 Hz
[3] The lowest uncertainty applies at the crossover frequencies. Uncertainties may be increased if the ac-dc differences are large or change with self-heating.
[4] See appropriate paragraph (e or f above).

A calibration service for ac-dc wattmeters will be provided on a special test basis. Direct inquiries to address given in the Appendix.

AC Resistors (1 to 0.001 Ω, 50 Hz to 10 kHz). Properly designed four-terminal ac resistors (having small phase angles) can be measured at current ratings not to exceed 50 A. The values for the in-phase and quadrature component can be reported for frequencies up to and including 10 kHz.

References

[1] **An investigation of multijunction thermal converters,** F. L. Hermach and D. R. Flach, *IEEE Trans. Instrum. Meas.* **IM-25,** No. 4, 524-528 (Dec. 1976).

[2] **Ac-dc comparators for audio-frequency current and voltage measurements of high accuracy,** F. L. Hermach, *IEEE Trans. Instrum. Meas.* **IM-25,** No. 4, 489-494 (Dec. 1976).

[3] **Thermal current converters for accurate ac current measurements,** E. S. Williams, *IEEE Trans. Instrum. Meas.* **IM-25,** No. 4, 519-523 (Dec. 1976).

[4] **Ac-dc transfer instruments for current and voltage measurements,** F. L. Hermach, *IRE Trans. Instrum.* **I-8,** 235 (1958).

[5] **Thermal converters for audio frequency voltage measurements,** F. L. Hermach and E. S. Williams, *IEEE Trans. Instrum. Meas.* **IM-15,** 260 (1966).

F. Instrument Transformers and Comparators

1. Voltage Transformers

NBS provides routine services for measurement of complex voltage ratios (magnitude and phase angle) of transformers for primary voltages up to 50 kV at 60 Hz. The estimated limit of measurement uncertainty is 0.01 percent for ratio and 0.1 mrad (1 mrad = 3.438 min) for phase angle for stable transformers tested with low burdens. Inquiries are invited concerning related measurements at higher voltages, and at frequencies other than 60 Hz, not listed in the present Appendix.

The following test information must be furnished for each transformer or for each range on a multirange transformer.

1. Frequency
2. Secondary voltages
3. Secondary burdens

Ambiguity of test burdens can be avoided if the impedance and power factor or the resistance and reactance, rather than volt-ampere rating, of each burden is specified.

Measurements are made with one side of both the primary and secondary windings connected to ground.

Reference

[1] **A wide range high-voltage capacitance bridge with one ppm accuracy,** O. Petersons and W. E. Anderson, *IEEE Trans. Instrum. Meas.* **IM-24,** No. 4, 336-344 (Dec. 1975). (Calibrations of voltage transformers at NBS are performed with the bridge described in this paper.)

2. Current transformers

Normally the Bureau calibrates only current transformers of high quality for use as reference standards. The Bureau may decline requests for tests which are not to be used for establishing or checking a reference standard. If the transformer quality is stated in terms of ANSI accuracy classes, calibration will be limited to transformers stated to be in the 0.3 percent class for one or more ANSI burdens. Bureau equipment is designed primarily for testing current transformers whose rated secondary current is 5 A. Results obtained at frequencies near 60 Hz normally will be reported to an uncertainty of 0.01 percent in ratio and 100 μrad (approximately 0.3 min) in phase angle.

Tests cannot be started until information is furnished concerning the following conditions: (1) test frequency, (2) secondary test currents, (3) secondary burdens, (4) ranges to be tested. It is customary to make tests at secondary currents of 0.5, 1, 2, 3, 4, and 5 A.

Transformer Burden: Current transformers should be tested with burdens equivalent to the impedance imposed when the transformer is used as a reference standard. Inclusion of tests at ANSI burdens is not recommended. The burdens listed in the Standard for Instrument Transformers, C-57.13, are for rating purposes only and differ from the instrument burdens imposed on a reference standard. Large errors in measurement can result if the values of ratio and phase angle obtained with an ANSI burden are used for the transformer when it supplies only an instrument burden.

Preferably the burden should be specified in terms of the measured resistance and inductance, including the leads to connect the instruments to the secondary of the transformer. If this measurement cannot be made conveniently, it will suffice in most cases to state the name of the maker, the type, range, and serial number of each instrument used in the burden, and the length and size of the wire of the leads used in the secondary circuit. Alternatively, the burden may be stated in terms of the volt-amperes and power factor of the secondary circuit at the test frequency.

The test equipment regularly used at the Bureau imposes a minimum test burden of about 0.03 Ω with a minimum inductance of about 10 μH.

Demagnetization: Unless otherwise specified, current transformers will be demagnetized before being tested. If it is desired to have a transformer tested as submitted (without demagnetization), this fact should be stated specifically.

Test limitation at frequencies greater than 60 Hz: At 400 Hz, the maximum current range for which tests are made is about 200 A and normally the values are reported to an accuracy of 0.02 percent for ratio and 200 μrad for phase angle. At 800 Hz there is a further reduction in the current range and accuracy.

Recalibration: At room temperature the ratio and phase angle under a specified test condition should be repeatable unless the core is magnetized. Once stability has been demonstrated, a current transformer should not require recalibration at intervals less than 5 years.

Contact resistance: Loose or dirty primary and secondary terminations may contribute appreciably to the calibration values obtained. These surfaces should be cleaned thoroughly prior to shipment for test to avoid additional errors.

References

[1] **An electronic ratio error set for current transformer calibrations,** R. L. Kahler, *IEEE Trans. Instrum. Meas.* **IM-28,** No. 2, 162-164 (June 1979).

[2] **A wide range current comparator system for calibrating current transformers,** T. M. Souders, *IEEE Trans. Power Appar. Syst.* **PAS-90,** No. 1, 318-324 (Jan./Feb. 1971).

[3] **Wide-band two-stage current transformers of high accuracy,** T. M. Souders, *IEEE Trans. Instrum. Meas.* **IM-21,** No. 4, 340-345 (Nov. 1972).

G. High-Voltage and Energy Measurements

1. Voltage Dividers and Resistors

Methods and equipment are available at the National Bureau of Standards for the measurement of voltage ratios with high accuracy, and a regular calibration service is provided for certain types of voltage dividers which are sufficiently stable for use as reference standards.

DC High-Voltage Dividers and Resistors

Resistive dividers and resistors designed for use at high-voltage levels are accepted for calibration only if they are nearly corona-free at the rated operating voltage and are designed to have small temperature and voltage coefficients. These coefficients should be sufficiently small so that the combined effects of temperature and voltage should not influence the ratio or resistance value of a device by more than 0.1 percent over the normal range of operating voltages. At a given voltage, dividers and resistors should not exhibit instabilities in their ratio or resistance values in excess of 0.005 percent.

AC High-Voltage Dividers

AC high-voltage dividers of sufficient quality to be considered as transfer standards will be tested at 60 Hz at voltages up to 100 kV rms.

There are high-voltage dividers which, although they perform satisfactorily as standards under dc voltage, are not considered suitable as transfer standards under 60 Hz ac conditions. The design of an ac divider requires special care not required for dc dividers. In particular, ac dividers which are designed to be transfer standards may have to be equipped with external shielding in order to minimize the effect of stray capacitive coupling to surrounding objects.

If the device is not properly shielded, the effects of proximity to surrounding objects and pickup from high-voltage conductors can introduce large uncertainties in the divider ratio. In such cases, the measurement of the ratio for one laboratory configuration would not necessarily be valid for another configuration, and consequently a meaningful calibration of the device is made difficult or impossible.

Therefore, NBS recommends that preliminary proximity tests be performed before an ac divider is submitted for test, in order to determine the suitability of the device as a transfer standard. The divider should be placed about 2.0 m from a vertical ground plane as measured from the center of the device. The divider should then be energized to some safe voltage level and the divider ratio should be measured. The measurement should then be repeated with the vertical ground plane (or divider) moved into a position 1.2 m from the center of the divider. If the divider ratio, at the same applied high voltage, changes by 0.1 percent, or more, then the device has excessive capacitive coupling and is not suitable as a transfer standard.

To test for pickup, remove the high-voltage connection to the top of the divider and then connect the top of the divider to ground with a thin wire. Measure the output voltage of the divider under these conditions both with and without the high-voltage source energized. If the resulting change in the output voltage exceeds 0.1 percent of the expected output voltage when the high voltage is connected to the divider, then again there is excessive coupling indicating that the device is not suitable as a transfer standard.

Whenever a high-voltage ac divider is sent to NBS, it will first be subjected to tests like those described above. If in our laboratory it shows variations in the measured ratio of more than 0.1 percent for either proximity or pickup, then no further tests will be performed and the device will be returned. The customer will be charged for the cost of these tests (minimum fee $500).

High-Voltage Pulse Dividers

Ratios of resistive, capacitive or mixed-voltage dividers are determined under pulsed high-voltage conditions. Determinations employ specially designed pulse dividers and calibrated Kerr cells as reference standards. Pulses applied during calibration are intended to simulate the divider's routine operation. Calibrations are made at selected voltage intervals up to 300 kV as requested.

Dividers Used to Measure High Voltage in Diagnostic X-Ray Units

The calibration of dividers used to measure the high voltage in diagnostic x-ray units consists of three measurements. These are the measurements of the variation of the ratio with a change in the frequency of the applied voltage in the frequency range of dc up to 10,000 Hz; a determination of the ratio under direct voltage at 25 kV; a measurement of any voltage induced variation of the ratio in the voltage range from 20 to 70 kVp.

References

[1] **X-CAL—A calibration system for electrical measurement devices used with diagnostic x-ray units,** R. H. McKnight and R. E. Hebner, *NBSIR 79-2072,* 74 pages (June 1980).
[2] **Evaluation of a multimegavolt impulse measurement system,** R. E. Hebner, D. L. Hillhouse, and R. A. Bullock, *NBSIR 79-1933,* 97 pages (Nov. 1979).
[3] **Calibration of high-voltage pulse measurement systems based on the Kerr effect,** *NBSIR 77-1317,* 33 pages (Sept. 1977).
[4] **Special shielded resistor for high-voltage measurements,** J. H. Park, *J. Res. Natl. Bur. Stand. (U.S.),* **66C,** No. 1, 19-24 (Jan.-Mar. 1962).

2. High-Voltage Capacitors and Capacitance Bridges

Calibration services are provided for capacitors and capacitance bridges having voltage and/or current ratings beyond the capability of the facilities used in providing the services described above (i.e., voltages >100 V at 60 Hz). Gas-dielectric capacitors (values to 1000 pF), and high-voltage capacitance bridges can be calibrated at 60 Hz. Other frequencies are also available at reduced voltages. Power factor correction capacitors rated up to 1000 μF and 10 kVA can also be calibrated at 60 Hz. The above calibrations are special, and advance arrangements must be made. For devices exceeding the above voltage, current, or kVA ratings, see "High-Voltage Field Calibrations" below.

References

[1] **A wide-range high-voltage capacitance bridge with one ppm accuracy,** O. Petersons and W. E. Anderson, *IEEE Trans. Instrum. Meas.* **IM-24,** No. 4, 336-344 (Dec. 1975).
[2] **An international comparison of high-voltage capacitor calibrations,** W. E. Anderson, R. S. Davis, O. Petersons, and W. J. M. Moore, *IEEE Trans. Power Appar. Syst.* **PAS-97,** No. 4, 1217-1223 (July/Aug. 1978).

3. Kerr Electro-Optical Pulse-Voltage-Measuring Systems

Calibration services are provided for Kerr cells used for electro-optical measurement of high-voltage pulses. The Kerr cell constant is determined by reference to calibrated pulse-voltage measurement systems. Calibrations can be performed for Kerr cells designed for measurement of pulse voltages peaking as high as 300 kV. Service is provided on a special test basis. (Listed in the Appendix under "High-Voltage and Energy Measurements.")

References

[1] **Recent refinements and developments in Kerr system electrical measurement techniques,** E. C. Cassidy, W. E. Anderson, and S. R. Booker, *IEEE Trans. Instrum. Meas.* **IM-21,** No. 4, 504-510 (Nov. 1972).
[2] **Calibration of high-voltage pulse measurement systems based on the Kerr effect,** R. E. Hebner and M. Misakian, *NBSIR 77-1317,* 33 pages (Sept. 1977).

4. High-Voltage Field Calibrations

Calibration services are provided for devices such as standard capacitors, dividers, inductive and capacitive voltage transformers, bridges, and power factor correction capacitors whose physical size and/or voltage and power ratings exceed the capabilities of NBS in-house facilities or preclude shipment to NBS. Calibration can be carried out in the client's laboratory or plant, in a mutually agreed-upon commercial, governmental, or university laboratory, or in special cases, in the field. Charges for the service will be actual expenses. These include preparation and shipping of test gear, travel and living expenses for test personnel, data analysis and report writing, and overhead. Since this is a special service, prior consultation and arrangement is essential. However, use of this service is strongly encouraged.

NBS has also developed a mobile system for the precise calibration of CCVT's, coupling-capacitor voltage transformers, used by the electric power industry for metering. This precision system can be transported via van to the power station site of CCVT's. The calibration unit is then assembled and placed in parallel with the transformer to be calibrated. The outputs of the two devices are compared to obtain the precise ratio of the device under test.

References

[1] **A prototype system for on-site calibration of coupling capacitor voltage transformers (CCVTS),** D. L. Hillhouse, O. Petersons, and W. C. Sze, *IEEE Trans. Power Appar. Syst.* **PAS-98,** No. 3, 1026-1036 (May/June 1979).

[2] **A prototype field calibration system for coupling capacitor voltage transformers (CCVTS),** D. L. Hillhouse, O. Petersons, and W. C. Sze, EL-690 Final Report Project 134-1, Electric Power Research Institute, Palo Alto, CA, 193 pages (Apr. 1978).

5. Watthour Meters

Only portable standard watthour meters (rotating standards) will be accepted for test, which consists of determinations of the percentage registration of the meter "as received." If meters are to be cleaned and adjusted this must be done before they are submitted for test. The Bureau does not undertake the cleaning and adjustment of meters and does not knowingly begin tests on faulty meters. Before tests can be started the test conditions must be completely specified by the user as to current and voltage ranges to be tested, frequency, applied voltage and current, and power factor. A guide listing a limited yet adequate schedule of tests is available at no charge. Test voltages should be chosen from the following values: 1, 2, or 4 times 110, 115, 120, 125, and 130 V (but not to exceed 480 V). Test currents should be chosen from the following values: 1, 10, or 100 times 0.5, 0.75, 1, 1.25, 1.5, 2, 2.5, 3, 3.75, 4, 5, 7.5 A (but not to exceed 100 A). Unless otherwise specified, test runs on portable standard watthour meters (rotating standards) are of approximately 100-s duration. The meters are energized for at least 1 h at rated voltage and current on one range before starting the test. Normally values are reported with an uncertainty of ± 0.05 percent.

The NBS Measurement Assurance Program (MAP) for electric energy (NBS Technical Note 930) is designed to evaluate energy-measuring equipment. An NBS-owned transport standard watthour meter (WHM) is shipped to a customer, and a tie to the U.S. national energy unit is made without the down-time encountered when WHM's are calibrated at NBS. In addition, and more important, for those who calibrate reference standard WHM's, a MAP standard can be used to evaluate an entire measuring system. By request, for smallest uncertainties, the MAP transfer standard WHM's can be calibrated by means of the current comparator system used to establish the unit of energy. Tests are made at 5 A, 120 V, unity and 0.5 pF, current lagging voltage.

References

[1] **A measurement assurance program for electric energy,** N. M. Oldham, *Natl. Bur. Stand. (U.S.), Tech. Note 930,* 17 pages (Sept. 1976).

[2] **Sampling techniques for electric power measurement,** R. S. Turgel, *Natl. Bur. Stand. (U.S.), Tech. Note 870,* 31 pages (June 1975).

[3] **Transfer of the kilowatthour,** S. R. Houghton, *IEEE Trans. Power Appar. Syst.* **PAS-94,** No. 4, 1232-1240 (July/Aug. 1975).

[4] **A current comparator system to establish the unit of electrical energy at 60 Hz,** K. J. Lentner, *IEEE Trans. Instrum. Meas.* **IM-23,** No. 4, 334-336 (Dec. 1974).

H. Data Converters

The NBS calibration service for data converters is described in detail in NBS Technical Note 1145, "A Calibration Service for Analog-to-Digital and Digital-to-Analog Converters."

The principal error parameters measured are those of linearity and differential linearity. Nevertheless, gain and offset errors may also be measured when appropriate, and the equivalent rms input noise of ADC's can be measured as well, provided it has essentially a Gaussian distribution. Determination of monotonicity in DAC's and missing codes in ADC's is not

generally performed since it requires excessive measurement time for high-resolution converters. These characteristics can often be inferred, however, from the linearity data available. Sensitivity of these various parameters to changes in temperature and power supply voltage, for example, is also not generally determined.

Since no standards for data-converter terminology exist, the definitions of these parameters follow:

Linearity Error: The difference between the actual and ideal levels of the static input/output characteristic after offset and gain errors have been removed.

Differential Linearity Error: The difference between the actual and ideal separation between adjacent levels.

Offset Error: The difference between the actual and ideal levels, measured at the negative-most level of the input/output characteristic. (Due to practical considerations, this definition is modified to the 2d most negative level, i.e., with the least significant bit (LSB) on.)

Gain Error: The difference between the actual and ideal levels, measured at the positive-most level of the input/output characteristic, after the offset error has been removed. (Again, in practice, a defining level is chosen slightly below the one stated here.)

Equivalent RMS Input Noise: The rms value of the effective internal noise of an ADC, referred to its input terminals.

In each of these definitions, the specified levels are taken to be: for DAC's, the discrete output levels, and for ADC's, the analog input levels at which the digital output transitions between adjacent codes occur. In this latter case, the transition levels are defined by the upper digital code of the transition in question.

(1) Linearity

For the linearity test, all 1024 digital codeword combinations of the 10 most significant bits are measured. Errors contributed by the remaining less significant bits are generally insignificant, a premise which is tested during the calibration process. The data are numerically processed to determine the maximum, minimum, and rms errors of the 1024 tested codes, and to determine, on a least-squares basis, individual correction coefficients for the ten most significant bits. The residuals from the computation of correction coefficients are a direct measure of the converter's superposition errors. These are computed as well.

(2) Differential Linearity

Differential linearity errors are measured at 2(N–1) major codeword transitions, for an N-bit converter.

(3) Offset & Gain

In general, converter offset and gain measurements are not required, since it is common practice to provide adjustable trimmer circuits which are periodically set to suit individual system requirements. If, however, accurate voltage measurements directly traceable to legal standards are required, then such measurements can be provided. Offset and gain errors are measured directly by setting the test converter to the designated code and measuring the input (or output) voltage by direct comparison with a transfer standard calibrated by NBS.

(4) RMS Input Noise

The equivalent rms input noise of A/D converters can be measured either as an average value over the entire full-scale range of the converter, or as a function of codeword, at 64 randomly selected points. The measurement technique relies upon the assumptions that the noise has a Gaussian distribution, and that at the given sampling rate, successive values are uncorrelated. The validity of these assumptions is tested prior to performing the measurements.

(5) Specifications for Test Converters

To be compatible with the NBS data converter test set, test units must conform to the following general specifications:

- Nominal resolution from 12- to 18-bits

° Conversion rate of at least 10 kHz

° Binary coding format, including binary sign-magnitude, offset binary, 2's complement, 1's complement, and complemented versions of these.

° TTL compatibility

° Voltage ranges of 0–5 V, ±5 V, 0–10 V, ±10 V

° Maximum error including offset and gain, not to exceed 500 ppm.

(6) Systematic Uncertainties

The estimated limits of the systematic uncertainties in measuring the various converter error parameters are summarized in table 1 for a ±10 V range. Random errors of the measurement process necessarily include random variations in the test converter and are, therefore, individually evaluated for each test. Nevertheless, measurements on very stable (check standard) converters indicate the random errors contributed by the test set itself are substantially less than the respective systematic uncertainties listed in the table.

Table 1

Parameter	Estimated Systematic Uncertainty DAC's		ADC's	
Linearity Error	2.7 ppm	+ 0.04 LSB	4.7 ppm	+ 0.16 LSB
Differential Linearity Error	3.2 ppm	+ 0.04 LSB	5.2 ppm	+ 0.16 LSB
Offset Error[a]	3 ppm		3 ppm	+ 0.07 LSB
Gain Error[a]	6 ppm		6 ppm	+ 0.13 LSB
RMS Input Noise[b]	———		-100%; + (20% + 10 μV) Noise introduced by Test Set is approx., 30 nV/$\sqrt{\text{Hz}}$ in a 1 MHz BW.	

[a] Measured upon special request only, if no adjustable trimmers are provided for these parameters.
[b] Since the effective bandwidth of the test converter is generally unknown, the noise contribution from the test set cannot be determined. Therefore, only an upper limit can be accurately placed on the noise measurements.

(7) Preparation of Test Boards

In general, it will be the customer's responsibility to mount integrated circuit, hybrid, or modular test converters on suitable test boards, providing all required trimmer circuits, voltage references, input or output amplifiers, recommended power supply decoupling capacitors, and connectors for interfacing to the input/output lines. Fully self-contained converters need only be fitted with the necessary interfacing connectors. In so doing, the customer gains significant performance advantages while at the same time saving the additional fee which would otherwise be charged by NBS for performing this service. High-performance converters are often susceptible to small changes in grounding, routing of dynamic signal lines, capacitive loading, etc. Particularly with ADC's, signal dynamics is quite important, even for static testing, since the converter itself always operates at high speeds. When mounted by the customer, the test converter and its support circuitry can be laid out more closely to the way in which it will be used in practice, as well as to the specific recommendations of its manufacturer. The test results should, therefore, more closely describe the converter's *in situ* performance. Detailed type and wiring requirements for the interfacing connectors are available upon request.

References

[1] **A calibration service for analog-to-digital and digital-to-analog converters,** T. M. Souders, D. R. Flach, and B. A. Bell, *Natl. Bur. Stand. (U.S.), Tech. Note 1145,* 66 pages (July 1981). (This

reference provides a complete description of the calibration service.)
[2] **A 20-bit + sign, relay switched d/a converter,** T. M. Souders and D. R. Flach, *Natl. Bur. Stand. (U.S.), Tech. Note 1105,* 16 pages (Oct. 1979). (This describes the reference standard used in the calibration service.)
[3] **A technique for measuring the equivalent rms input noise of a/d converters,** T. M. Souders and J. A. Lechner, *IEEE Trans. Instrum. Meas.* **IM-29** (Dec. 1980).
[4] **A high-speed low-noise 18-bit digitial-to-analog converter,** H. K. Schoenwetter, *IEEE Trans. Instrum. Meas.* **IM-27** (Dec. 1978).
[5] **An automated test set for high resolution analog-to-digital and digital-to-analog converters,** T. M. Souders and D. R. Flach, *IEEE Trans. Instrum. Meas.* **IM-28** (Dec. 1979).

I. AC Voltage Calibrations in Range of 0.1 Hz-10 Hz

NBS offers a calibration service for ac voltage standards and rms voltmeters in the 0.1 Hz to 10 Hz range on a special test basis. The means for this service is an "AC Voltmeter/Calibrator," an NBS developed instrument containing a high resolution rms digital voltmeter and both ac (sine-wave) and dc voltage calibrators. Details of the calibration procedures employed in this service are described in ref. [3].

AC voltmeters can be calibrated at 0.1, 0.2, 0.5, 1, 2, 5, and 10 Hz using the ac voltage calibrator. The uncertainty, ϵ_s, of the ac calibrator voltage is within ±0.020 percent for voltage levels ranging from 0.5 mV to 7 V rms. The estimated uncertainty of a calibration point is $\pm(\epsilon_s + ts/\sqrt{N})$, where t is Student's t for the selected confidence level, s is the sample standard deviation over a series of measurements, and N is the number of measurements (test runs) used to obtain the mean values of the measured quantities (voltmeter readings).

AC voltage standards are calibrated in the 2 mV to 7 V range, using the rms voltmeter to compare the voltage V_T from the test unit with the voltage V_c of the same nominal level from the ac voltage calibrator. After the test runs are made, the average (V_c-V_T) is formed for each calibration point and "adjusted" if the frequency of V_T is significantly different from the calibrator frequency. Frequency response curves for the rms voltmeter are used to compute this adjustment. If the uncertainty in the calibrator voltage V_c and the uncertainty of the adjustment are denoted by ϵ_s and ϵ_a, respectively, the estimated uncertainty of a calibration point is given by $\pm(\epsilon_s+\epsilon_a+t\, s/\sqrt{N})$, where s is the standard deviation of a (V_c-V_T) comparison and N is the number of comparisons (test runs).

If the voltage standard is of a design which has inherently stable voltage with respect to frequency, a frequency response (relative voltage calibration may be preferable to a conventional voltage calibration. The user then establishes the voltage levels by calibrating the voltage at 10 Hz. Frequency response calibrations are usually made at the 1 V level using the rms voltmeter to compare the voltage from the standard under test with the voltage from the ac voltage calibrator at each frequency. After N comparisons at each frequency, the quantities $(V_c-V_T)_f$ are computed for each frequency, from which

$$(V_c-V_T)_{10} - (V_c-V_T)_f \simeq (V_f-V_{10})_T.$$

The estimated uncertainty of a calibration point $(V_f-V_{10})_T$ is $\pm[e_s+(t/\sqrt{N})(s^2_{10}+s^2_f)^{1/2}]$, where e_s (less than ±38 ppm) is the uncertainty in the frequency response of the calibrator voltage, and s_{10} and s_f are the standard deviations of a comparison for the first and second left-hand terms, respectively, of the above equation. Frequency response calibrations are limited to the nominal frequencies of the ac voltage calibrator.

Unless otherwise requested by the customer, a single accuracy of calibration will be given for the calibration points, based on a confidence level of 0.98 and the largest standard deviation encountered. It is expected that the value of N, requested by the customer, will generally be 3.4 or 5. Assuming a selected confidence level of 0.98, values of t corresponding to N equal to 3, 4, and 5 are approximately 7.0, 4.5, and 3.7, respectively.

References

[1] **An rms digital voltmeter/calibrator for very-low frequencies,** H. K. Schoenwetter, *IEEE Trans. Instrum. Meas.* **IM-27,** No. 3, 259-267 (Sept. 1978).

[2] **NBS provides voltage calibration service in 0.1-10 Hz range using ac voltmeter/calibrator,** H. K. Schoenwetter, *IEEE Trans. Instrum. Meas.* **IM-28**, No. 4, 327-331 (Dec. 1979).

[3] **AC voltage calibrations for the 0.1 Hz to 10 Hz frequency range,** H. K. Schoenwetter, to be published.

CHAPTER V

V. Electromagnetic Measurements at Radio, Microwave, and Millimeter Wave Frequencies

A. Introduction

The National Bureau of Standards provides methods and standards of measurement for electromagnetic quantities used in devices and systems in the electronics industries and in related fields. This support is provided as a function of frequency ranging from 100 kHz to optical frequencies. However, specific electromagnetic characteristics are usually not available as a continuous function of frequency except for limited portions of this frequency spectrum. Besides measurements requiring coherent frequency sources, pulse, noise and electromagnetic interference measurements are provided. As a result calibration and consultation services are available for voltage, power, attentuation, impedance, noise, fields and other electromagnetic quantities. Details on ranges and magnitudes for specific quantities are itemized in the service listings to follow below.

Special Instrumentation and Scheduling Requirements

In order to provide meaningful and reproducible (uncertainties minimized) electromagnetic measurements or calibrations the terminations and interfaces must be well characterized. Therefore standards, instruments, and devices submitted for calibration or evaluation, as a general rule, must be equipped with precision coaxial connectors or Electronic Industries Association standard rectangular waveguide sizes terminated with appropriate flanges. Terminations, frequency ranges, magnitudes and other details for a given type of service are stipulated in the Appendix and in service descriptions which will follow below. To improve service, reduce cost and turnaround time, and facilitate planning, some of the electromagnetic services are available only on a scheduling basis. If services are available on a scheduled basis the Appendix will so indicate for the quantity listed. Further considerations on terminations are as follows:

(a) Coaxial Connectors

In coaxial systems, the use of precision coaxial connectors is strongly advocated for calibrations involving immittance, attenuation, power, and other quantities. Precision coaxial connectors are those which meet or exceed the electrical and mechanical specifications set forth by the Institute of Electrical and Electronic Engineers [1,2]. As a general rule only those standards and instruments so equipped can be calibrated to the highest accuracies.

For immittance, the difference in calibration uncertainties may vary by as much as a factor of 10, depending upon whether the connectors on an item are of the precision or nonprecision type.

Similar advantages are realized in attenuation measurements where the voltage standing wave ratio (VSWR) of a mated pair of connectors is highly important. A typical measurement at 4 GHz might yield the following results: with precision sexless coaxial connectors, mismatch errors due to mated connector pairs are of the order of 0.01 dB as compared to 0.02 dB for the improved Type N and 0.05 dB for the ordinary Type N connectors. Systematic errors in the measurement system are about 0.03 dB. Therefore, the precision connector is a practical necessity for utilizing the full capabilities of the measurement system.

Calibrations involving power are not as critically dependent upon connector uncertainties because the VSWR of a connector pair need only be 1.03 or better to avoid significant uncertainties at the present state of the art. However, the use of precision connectors in power instrumentation provides assurance that connector VSWR's greater than 1.03 are not present to limit the best available performance.

References

[1] **Precision coaxial connectors (IEEE Standard 287-1968) (ANSI C16.43-1972),** (Institute of Electrical and Electronic Engineers, Inc., New York, NY).

[2] **B. O. Weinschel standardization of precision coaxial connectors,** *Proc. IEEE* **55,** 923 (June 1967).

(b) Rectangular Waveguides (Flange Terminations)

Each EIA designated waveguide size covers a range of frequencies. In general, the measurement systems provide complete and continuous coverage as appropriate for the various waveguide sizes. However, for some electromagnetic quantities an NBS automatic network analyzer is used. Details are provided in the sections to follow, describing the quantities for which services are available. Information concerning connectors, frequencies, and magnitudes also appears in the Appendix.

A common metrology practice employs the echelon or chain system of calibration with a degradation in accuracy in each step of the chain. Each succeeding laboratory is less accurate than the one from which it received its calibration. This degradation can be minimized if an operating laboratory maintains adequate control procedures and utilizes Measurement Assurance Programs (MAPs) available from NBS. It is intended that ultimately Measurement Assurance Programs will be available for critical electromagnetic quantities to allow laboratories to maintain these units with state-of-the-art uncertainty. The rate at which such programs are established is contingent upon the demand and the availability of NBS staff. As Measurement Assurance Programs become available they will be listed in the Appendix.

B. Attenuation Measurements

1. Special Attenuation Measurement Services and Consultation

The specific attenuation services listed below are available on a limited basis, depending on other demands and staff availability. Measurements not listed can be provided if sufficient advance notice is given and resources permit. The cost of such services must be negotiated and will, in general, be higher than other established services. Consultation by telephone or written correspondence as indicated in the Appendix is suggested. Often a measurement technique can be suggested that will permit the customer to perform his calibrations in-house with appropriate reference to other NBS supported standards. (Note the definitions given in sec. V.B.5.)

2. Attenuation Measurement of Coaxial Attenuators

Coaxial fixed and variable attenuators are measured on the NBS modified automatic network analyzer (ANA) over the frequency range 0.1 to 18 GHz as indicated in the Appendix (see Attenuation).

All measurements are made by the substitution method, which requires that the connectors used be asexual or that the attenuator have a male connector at one port and a female at the other. If an adapter is required to comply with the foregoing, it must be supplied with the attenuator. The combination will be calibrated as one unit.

In addition to measurements performed on the ANA, measurements at a fixed frequency of 30 MHz are available referenced to the NBS waveguide below cutoff standard at this frequency.

Limits of Uncertainty

Coaxial attenuators are normally measured in a system having a characteristic impedance of 50 Ω. Because measurement limits of uncertainty are degraded by any deviation from this characteristic impedance, the types of allowable connectors are limited. Connectors having a known plane of reference, such as the sexless precision connectors or Type N connectors meeting Mil C 39012, are acceptable. Limits of uncertainty also depend upon the VSWR of the individual attenuator, quality of the attenuator and connectors, and the magnitude of the attenuation [1]. Typical systematic uncertainties range from 0.03 to 0.05 dB/10 dB of attenuation.

3. Attenuation Calibrations of Variable Rectangular Waveguide Attenuators

Variable waveguide (usually rotary vane) attenuators are calibrated in the frequency bands indicated in the Appendix by the IF-Substitution technique referenced to 30 MHz, direct RF substitution or on the NBS modified ANA, as appropriate.

It is suggested that measurements requested be held to a minimum number of settings at a single band-center frequency, which should be sufficient to determine the characteristics of the device. It is further recommended that previously calibrated units not be resubmitted unless tests performed by the user indicate a shift in values.

Limits of Uncertainty

This is a function of resettability and input VSWR of the waveguide ports as well as internal leakage and quality of flanges. Devices submitted should be in the best possible condition to justify calibration and insure long-term stability of measured values. Typical systematic uncertainties range from 0.03 to 0.05 dB/10 dB of attenuation.

4. Attenuation Measurements of Waveguide Below Cutoff (Piston) Attenuators With Coaxial Connectors

Measurements on piston (WBCO) attenuators are performed at 30 MHz as indicated in the Appendix (see Attenuation). These attenuators are normally quite stable and seldom need recalibration unless damaged or mechanically worn. Since any laboratory can perform independent checks to determine continuing repeatability and linearity of attenuation, we do not recommend periodic NBS recalibrations. This recommendation, in part, is also because more damage is suffered in transit than in daily use. In any measurement, the maximum power delivered to the test attenuator will not exceed 400 mW. If the attenuator cannot tolerate this power level, some reduction of measurement range indicated in the Appendix will be required.

Limits of Uncertainty

These attenuators are normally calibrated in a system having a characteristic impedance of 50 Ω. Since only measurements of incremental attenuation are made on this type of attenuator, Type BNC, C, TNC, and similar connectors are acceptable, but precision connectors* are preferred to reduce leakage [1]. Limits of uncertainty depend upon the quality of the attenuator and connectors, as well as upon the VSWR of the attenuator, and the magnitude of attenuation. Typical systematic uncertainties range from 0.003 to 0.005 dB/10 dB of attenuation.

5. Definitions

Insertion loss—The 1977 edition of the *IEEE Standard Dictionary of Electrical and Electronics Terms* defines insertion loss as follows: (Waveguide Component). The change in load power due to the insertion of a waveguide or transmission-line component at same point in a transmission system, where the specified input and output waveguides connected to the component are reflectionless looking in both directions from the component (match-terminated). This change in load power is expressed as a ratio, usually in decibels of (A) the power received at the load before insertion of the waveguide or transmission line component to (B) the power received at the load after insertion. Note a more general definition of insertion loss does not specify match-terminated waveguides, in which case the insertion loss would vary with the load and generator impedances. Some workers in the field prefer to add the initial condition that the input and output waveguides connected to the component are lossless as well as match-terminated [2].

Standard attenuation—This is defined as the insertion loss of a linear two-port device in a nonreflecting system which is initially connected together at the insertion point by a standard connector pair (as defined earlier) or waveguide joint, the nonreflecting condition being obtained in the standard waveguide sections to which the standard connectors or waveguide joints are attached. The standard attenuation is the ratio expressed in decibels of the powers absorbed by the load before and after insertion of the two-port device being calibrated.

*Standard connector pair waveguide joint. A "standard connector" is one which is made precisely to standard specifications for the particular type of connector under consideration. Standard connector pairs usually have low but measurable loss and reflections [1,3,4].

Incremental attenuation—Incremental attenuation is the change in attenuation of an adjustable attenuator between a reference setting (usually zero) and any other setting. The same restraints on system conditions apply as for attenuation and standard attenuation. The term "differential attenuation" is sometimes applied to this case and usually refers to two non-zero settings.

References

[1] **Microwave attenuation measurements and standards,** R. W. Beatty, *Natl. Bur. Stand. (U.S.), Monogr. 97,* 50 pages (Apr. 3, 1967).

[2] **Basic theory of waveguide junctions and introductory microwave network analysis,** D. M. Kearns and R. W. Beatty, *Pergamon Press International Series of Monographs in Electromagnetic Waves,* **13,** 59-63 (1967).

[3] **Effects of connectors and adapters on accurate attenuation measurements at microwave frequencies,** R. W. Beatty, *IEEE Trans. Instrum.* **13,** 272-284 (Dec. 1964).

[4] **Insertion loss concepts,** R. W. Beatty, *Proc. IEEE* **52,** No. 6, 663-671 (June 1964).

6. Note:

Also see section I.3 for wideband attenuation or gain.

C. Electromagnetic Fields and Antenna Measurements

Measurement services are available for both directive and non-directive antennas, depending on design and quantity required, from 30 Hz to 75 GHz.

1. Measurement Services for Primarily Directive Antennas

Accurate measurement of antenna gain, pattern, and polarization are generally available from about 750 MHz to about 75 GHz. However, measurements of all three characteristics may not be practical for a given antenna because the measurement accuracy, capability, and cost depend on the frequency, type and size of antenna, and the parameters to be measured. Therefore, a particular measurement must be negotiated in advance. The following methods and facilities are used for these measurements.

(a) Planar Near-Field Scanning Method

With this technique, gain, pattern and polarization parameters are calculated from near-field amplitude and phase measurements taken over a plane area close to the test antenna. The absolute gain can be determined to within about ± 0.15 dB, the polarization axial ratio to within about ± 0.10 dB/dB and side lobe levels can be obtained down to -50 or -60 dB. (The exact uncertainties will depend on the frequency, type, size of antenna, etc.) Antennas with apertures up to about 3.5 m in diameter can be managed. Measurements can be made from 750 MHz up to 75 GHz.

References

[1] **Correction of near-field antenna measurements made with an arbitrary but known measuring antenna,** D. M. Kerns, *Electronics Letters 6,* No. 11, 346-347 (May 28, 1970).

[2] **New method of gain measurement using two identical antennas,** D. M. Kerns, *Electronics Letters* **6,** No. 11, 348-349 (May 28, 1970).

[3] **Recent experimental results in near-field antenna measurements,** R. C. Baird, A. C. Newell, P. F. Wacker, and D. M. Kerns, *Electronics Letters* **6,** No. 11, 349-351 (May 28, 1970).

[4] **Plane-wave scattering-matrix theory of antennas and antenna-antenna interactions: Formulation and applications,** D. M. Kerns, *J. Res. Natl. Bur. Stand. (U.S.),* **80B** (Math. Sci.), No. 1, 5-51 (Jan.-Mar. 1976).

(b) Extrapolation Range Measurements

In this method, the received signal transmitted between a pair of antennas is measured as a function of the separation distance between the antennas. The antennas need not be identical, and

no assumptions concerning the polarization are required. The method is not well suited for patter measurements, but it is the most accurate technique known for absolute gain and polarizatio measurements. Above 1 GHz, the accuracies are typically ±0.10 dB for gain measurements, an ±0.05 dB/dB for polarization axial ratio measurements. There are upper size limitations associate with existing NBS extrapolation ranges. These limitations depend on the type of antenna, th frequency, and the desired measurements and accuracies. Therefore, negotiations must be conducted prior to submitting antennas for calibration to ascertain if all requirements can be met.

Reference

[1] **Accurate measurement of antenna gain and polarization at reduced distances by an extrapolation technique,** A. C. Newell, R. C. Baird, and P. F. Wacker, *IEEE Trans. Antennas Propagat.* **AP-21,** No. 4, 418-431 (July 1973).

2. Measurement Services for Primary Non-Directive Antennas

In this category measurement services are offered for antennas, antenna systems, field strength measurement devices, and both electric (E) and magnetic (H) field probes and meters. The parameters that may be measured are antenna factor, antenna gain, antenna pattern, antenna polarization, frequency response, sensitivity, and linearity. Measurements of all these characteristics may not be practical because the accuracy, capability, and cost depend on the frequency, type of instrument, and selected parameters to be measured. Therefore, each particular test must be negotiated in advance. The following measurement methods and facilities are used for these.

(a) Measurement of Loop Antennas and Magnetic Field Probes

A field intensity meter with its antenna or a separate loop antenna is measured at the NBS field site by immersing the receiving antenna in the calculated near-zone magnetic field of a single-turn balanced loop. In the case when a high intensity field (e.g., above 0.3 mA/m free space magnetic field) is required for the measurement, a TEM (transverse electromagnetic) cell may be used for measuring relatively small probes.

References

[1] **The near-zone magnetic field of a small circular loop antenna,** F. M. Greene, *J. Res. Natl. Bur. Stand. (U.S.),* **71C** (Eng. and Instr.), N0. 4 (Oct.-Dec. 1967).

[2] **Calibration principles and procedures for field strength meters (30 MHz to 1 GHz),** H. E. Taggart and J. L. Workman, *Natl. Bur. Stand. (U.S.), Tech. Note 370* (Mar. 1969).

(b) Measurement of Electric Field Antennas and Probes

A receiving antenna such as a dipole or log periodic, or a field strength meter for measuring the electric field component, or an E-field probe may be measured. An open-site range is used for generating a known horizontally-polarized electric field in the a frequency range of 30 to 300 MHz. An indoor anechoic chamber is used for frequencies from 200 MHz to 18 GHz. In either case, the far-zone radiated field is established in terms of the measured open-circuit voltage detected by a standard NBS self-resonant receiving dipole.

References

[1] **Calibration principles and procedures for field strength meters (30 MHz to 1 GHz),** H. E. Taggart and J. L. Workman, *Natl. Bur. Stand. (U.S.), Tech. Note 370* (Mar. 1969).

[2] **NBS field strength standards and measurements (30 MHz to 1000 MHz),** F. M. Greene, *Proc. IEEE***55,** 970-981 (June 1967).

[3] **Field strength above 1 GHz: Measurement procedures for standard antennas,** R. R. Bowman, *Proc. IEEE* **55,** 981-990 (June 1967).

(c) Measurement of Monopole-Type Antennas and Probes in a Vertically-Polarized Electric Field

A monopole antenna or field strength meter for receiving vertically-polarized waves may be measured on a 100×200 ft ground screen. A known radiated field is generated by a thin transmitting monopole in terms of the measured base current at frequencies from about 10 kHz to 300 MHz.

References

[1] **Electromagnetic waves and radiating systems,** E. C. Jordan, Prentice-Hall, Inc. (1950).

[2] **Antennas, theory and practice,** S. A. Schelkunoff and H. T. Friis, John Wiley & Sons, Inc. (1952).

[3] **Generation of standard EM field using TEM transmission cells,** M. L. Crawford, *IEEE Trans. Electromag. Compat.* **EMC-16,** No. 4, pp. 189-195 (Nov. 1974).

(d) Measurement of Microwave "Hazard Meters" and Similar Types of Radiation Monitors and rf Probes

The measurement of antennas and field strength meters for measuring relatively high-intensity fields at frequencies from 200 MHz to 18 GHz is accomplished in the NBS anechoic chamber. The probe or antenna to be measured is immersed in the field generated by a transmitter and open-end waveguide or pyramidal horn. The power density in the center of the transmitted beam is determined from the measured value of net transmitted power, known (near-zone) gain of transmitting antenna, and separation distance.

It is also possible to measure various response patterns of an rf radiation monitor or special transmitting antenna, such as the E plane or H plane of S plane pattern, or to evaluate the directional properties of an isotropic antenna.

The overall "worst-case" uncertainty of a measurement in the anechoic chamber is approximately 0.7 to 1.5 dB. The measurement system is not yet characterized well enough to furnish exact statistical error limits.

Reference

[1] **Design and calibration of the NBS isotropic electric-field monitor (EFM-5), 0.2–1000 MHz,** E. B. Larsen and F. X. Ries, *Natl. Bur. Stand. (U.S.), Tech. Note 1033* (Mar. 1981).

Summary of non-directive antenna measurements for radiated field strength measurements

Field parameter	Type of Measurement Facility	Frequency range	Radiating antenna source
H (near zone)	Wood building	30 Hz – 50 MHz	Loop (20 cm)
E (vertical)	Open site (ground screen)	10 kHz – 30 MHz	Short monopole
E (vertical)	Open site (ground screen)	30 – 300 MHz	$\lambda/4$ monopole
E (horizontal)	Open site	30 – 300 MHz	Receiving $\lambda/2$ dipole
Power density	Anechoic chamber	200 – 500 MHz	Open-end wave guide
		0.5 – 18 GHz	Pyramidal horn

For guided-wave field strength measurements (applicable to physically small antennas)

Field parameter	Transmission line used	Frequency range	Principal measured quantity
E or H	TEM cells	10 kHz – 500 MHz	Voltage or power
E or H	Waveguide cells	300 – 1100 MHz	Power

D. Impedance and/or Reflection Coefficient

Services provided in this category are for passive devices over the frequency range from 30 kHz to 65 GHz. Specific frequencies where calibrations are available are listed in the Appendix. Highest accuracy is obtained only for standards equipped with precision coaxial connectors or waveguide flanges. Standards submitted for calibration should be in good repair and except for very minor cleaning of connector surfaces, should require no precalibration maintenance. NBS does not provide repair services so that items received which require maintenance will be returned to the sender and a handling fee will be charged.

Calibration service for measuring instruments such as bridges or meters is not provided. It is recommended that the accuracy of these instruments be verified by the owner through the use of stable standards especially selected for particular values and frequencies appropriate to the instrument in question.

Measurement Conditions

All calibrations are performed under typical ambient laboratory conditions of 23 °C, and an atmospheric pressure of approximately $(8.4 \pm 0.2) \times 10^4$ Pa. Services at ambient conditions outside these limits is not provided. Also the power applied to any device being calibrated does not exceed 1 W. Additional information pertaining to immittance (impedance and admittance) measurement and standards is contained in the following references.

References

Lumped Parameter

[1] **The measurement of lumped parameter impedance: A metrology guide,** R. N. Jones, *Natl. Bur. Stand. (U.S.), Monogr. 141,* 211 pages (June 1974).

[2] **Impedance of lumped circuits,** L. E. Huntley and R. N. Jones, *Proc. IEEE* **55,** No. 6, 900-911 (June 1967).

[3] **A technique for extrapolating the 1 kc values of secondary capacitance standards to higher frequencies,** R. N. Jones, *Natl. Bur. Stand. (U.S.), Tech. Note 201,* 15 pages (Nov. 1963).

[4] **A precision, high frequency calibration facility for coaxial capacitance standards,** R. N. Jones and J. E. Huntley, *Natl. Bur. Stand. (U.S.), Tech. Note 386,* 27 pages (Mar. 1970).

[5] **Standards for the calibration of Q-meters, 50 kHz to 45 MHz,** R. N. Jones, *J. Res. Natl. Bur. Stand. (U.S.),* **58C** (Eng. and Instr.), No. 4, 243-248 (Oct.-Dec. 1964).

[6] **Evaluation of three-terminal and four-terminal pair capacitors at high frequencies,** R. N. Jones, *Natl. Bur. Stand. (U.S.), Tech. Note 1024,* 15 pages (Sept. 1980).

Coaxial

[1] **Impedance measurements in coaxial waveguide systems,** R. L. Jesch and R. M. Jickling, *Proc. IEEE* **55,** No. 6, 912-923 (June 1967).

1. Special Measurement Services and Consultation on Measurement Problems

Regular established calibration services for impedance standards are generally described in succeeding paragraphs and specific information is provided in the Appendix (see Impedance).

2. Capacitance, Two-Terminal, Low-Loss

In the frequency range from 30 kHz to 250 MHz, capacitance calibrations to a minimum uncertainty of ±0.1 percent are available from 1 pF to 1 μF depending upon frequency. The upper capacitance limit for calibration decreases as the frequency increases and is 50 pF at 5 MHz and above. (See refs. [1], [2], and [3] above.)

At 1 MHz a special high accuracy service is available for capacitors with nominal values of 50, 100, 200, 500 and 1000 pF provided they are equipped with 14 mm coaxial connectors. See Appendix (Impedance) for additional requirements. (See ref. [4]).

Reports of calibration for capacitors normally do not give conductance values. This is because capacitors of standard quality, especially those with air-dielectric, have conductance values too small to be measured accurately at the present state-of-the-art.

Reference

A technique for extrapolating the 1 kHz values of capacitance standards to higher frequencies is described by R. N. Jones in NBS Technical Note 201 (Nov. 1963). This reference describes a technique for obtaining a high frequency value of a capacitor equipped with an unshielded (banana plug) connector. The measurement technique yields effective capacitance values at high frequencies using the capacitance value at 1 kHz and the residual series inductance. The same technique, with some modifications, is useable for three-terminal and four-terminal pair capacitors. NBS Technical Note 1024 (Sept. 1980), also by R. N. Jones, describes this procedure. It is emphasized that these extrapolation procedures are only useable for air dielectric capacitors or capacitors with insulating materials whose dielectric constant does not change with frequency.

3. Capacitance Three-Terminal Low-Loss

Services are available at 100 kHz, 465 kHz and 1 MHz for capacitors having values of 10, 100, and 1000 pF. Calibration uncertainty is typically ±0.06 percent for all frequencies and values except for 1000 pF at 1 MHz where the uncertainty is nominally ±0.1 percent.

Fixed value reference standards are maintained by NBS for values of 10, 100, and 1000 pF. High quality three-terminal air dielectric capacitance standards should have low residual series inductance (⩽0.1 μH). This being the case, it may be assumed that to an accuracy of ±0.10 percent, the capacitances of standards of 1 pF or less with air dielectric is the same at 1 MHz as it is at 1 kHz. Thus, it is unnecessary to have capacitors smaller than 10 pF calibrated at 1 MHz.

4. Inductors, Two-Terminal, High-Q

In the frequency range from 10 kHz to 250 MHz, inductance calibrations to a minimum uncertainty of ±0.1 percent are available from 0.01 μH to 1 H. The upper inductance limit for calibration decreases as the frequency increases and is 1 μH at 250 MHz. In the Report of Calibration, the resistance of the inductor is also given. Service is available only for aircore inductors or inductors whose value is independent of current.

5. Resistors, Two-Terminal, Low-Q

In the frequency range from 30 kHz to 250 MHz resistance calibrations to a minimum uncertainty of ±0.1 percent are available from 0.1 Ω to 10 MΩ. At higher frequencies the upper limit for resistance decreases and is 20 kΩ at 250 MHz. Calibration services for resistors less than 20 kΩ are not available at frequencies above 2 MHz.

Reports of Calibration for resistors will include the inductance or capacitance associated with the resistor. Equivalent series values are normally given for inductive resistors and equivalent parallel values for capacitive resistors.

6. Q-Standards

Standards for Q-measurements are maintained at NBS. These are high Q-inductors equipped with banana plug connectors at a spacing of 1 inch on centers. These standards have inductance values of 0.25, 2.5, 25, 250, 2500 and 25,000 μH, and effective Q-values from 100 to approximately 600. These serve as working standards for calibration of Q-standards of a similar type. Calibration

frequencies range from 50 kHz to 45 MHz. The calibration report includes effective resonating capacitance and effective Q. Uncertainties are of the order of ±0.2 percent for capacitance and 2 percent for Q. Provisions are made for calibrating each Q-standard at three frequencies; however, adequate assurance of stability is usually provided by recalibrating only at the center frequency.

Limits of Uncertainty

Estimated limits of uncertainty are based upon a statistical analysis of previously obtained calibration data. These uncertainties are believed to result solely from sources of random error as opposed to known systematic errors.

Reference

[1] **Standards for the calibration of Q-meters, 50 kHz to 45 MHz,** R. N. Jones, *J. Res. Natl. Bur. Stand. (U.S.),* **58C** (Eng. and Instr.), No. 4, 243-248 (Oct.-Dec. 1964).

7. Standards for Distributed Parameter Measurement

Depending upon the application, lumped parameter impedance standards such as capacitors, inductors, and resistors are replaced by distributed parameter devices in coaxial systems in the region of 100 to 300 MHz. This brings about the need for standards of impedance magnitude and phase angle, voltage standing wave ratio (VSWR), phase shift, and length of equivalent air-dielectric transmission line. Services of this type extend from 0.1 to 8 GHz.

Coaxial Impedance Measurements

Services are available for complex impedance and reflection coefficient, voltage standing wave ratio (VSWR), insertion phase, and length of equivalent air-dielectric transmission line. The length of equivalent air line is defined as the length of a section of lossless reference coaxial air line required to produce the same total insertion phase as the item being measured.

General

Measurements on coaxial devices in the frequency range 0.1 to 18 GHz are made on the NBS modified Automatic Network Analyzer (ANA).

A short or open-circuit termination may be furnished with calibration items requiring measurement of impedance, phase shift, and length of equivalent airline in order to establish a reference plane, reproducible by the customer. VSWR measurements are normally referenced to 50 Ω.

The calibration services usually apply to determining the impedances or VSWR of standard terminations and mismatches, or to determining the length of sections of precision coaxial air-dielectric transmission line.

Reference

[1] **Impedance measurements in coaxial waveguide systems,** R. L. Jesch and R. M. Jickling, *Proc. IEEE* **55,** No. 6, 912-923 (June 1967).

Reflection Coefficient Magnitude Measurements of Reflecting and Nonreflecting Waveguide Ports

Waveguide ports are measured in a reflectometer system relative to a sliding short or sliding load in a precision section of waveguide.

Some measurements in waveguide bands below 18 GHz are performed on the NBS modified Automatic Network Analyzer (ANA) while all of those above 18 GHz are performed on manual fixed-frequency systems. (See Appendix.)

It is recommended that previously calibrated units not be resubmitted unless tests performed by the user indicate a shift in values.

The reflectors must be fitted with standard waveguide flange-type connectors. The faces of these flanges should be machined flat and smooth and should not contain protrusions or

indentations. Considerable care must be exercised in keeping the mating connector flange surfaces smooth and clean. Accurate alignment of the interior surfaces of the joining waveguides at the flange junction also is very important. The back of the flange which makes contact with the connecting bolts should be nominally flat and free of soft materials including paint. The connecting holes of the flange should be symmetrically and accurately aligned to the rectangular waveguide opening. These precautions must be observed when using a waveguide port in a precision measurement system.

The term nonreflecting as used here indicates that the waveguide port has been designed or adjusted with the intent to produce a reflection coefficient magnitude, $|\Gamma|$, equal to zero. Although most waveguide ports for such applications cannot produce a reflection coefficient magnitude identically equal to zero, their reflection coefficient magnitudes often approach zero very closely.

Limits of Uncertainty

Assigned limits as noted in the Appendix depend upon the quality of the flanges as well as the numerical value of reflection coefficient magnitude. Systematic errors assigned by NBS vary with waveguide size and relate to absolute dimensions of the precision waveguide sections and internal surface finish.

Reference

[1] **A guide to the use of the modified reflectometer technique of VSWR measurement,** W. J. Anson, *J. Res. Natl. Bur. Stand. (U.S.),* 65C (Eng. and Instr.), No. 4, 217-223 (Oct.-Dec. 1961). (The measurement technique utilized in reflection measurements is described in this paper.)

E. Noise Temperature Measurements

Definition

The Effective Noise Temperature, T_{ne}, is proportional to the power emerging from the output port of the coaxial or waveguide noise source when it is connected to a nonreflecting load. The noise temperature, T, of the noise source is analogous to the available power [1,2] from a source and is obtained when corresponding reflection coefficients for source and load are complex conjugates of each other (characteristic impedances being chosen real). The relationship between the noise temperature and effective noise temperature is

$$T_{ne} = T[1-|\Gamma|^2]$$

where $|\Gamma|$ is the reflection coefficient magnitude of the coaxial or waveguide noise source, and T_{ne} and T are in kelvins.

General

Coaxial Noise Sources:

(1) Effective noise temperature measurements are made on one-port devices that serve as coaxial noise sources under conditions of continuous, unmodulated operation.

(2) In noise sources utilizing a gas-discharge tube, the tube should be securely fitted into a mount terminated at the cathode end with a suitable matched load. Direct current required for the tube should not exceed 300 mA but should be sufficient to prevent excessive plasma oscillations. Complete information on the operating current of the tube and a wiring diagram of the noise source must be supplied.

(3) In noise sources utilizing a temperature-limited diode, the diode should be securely fitted into a mount terminated at the cathode end with a suitable matched load. Complete information on the operating current of the tube and a wiring diagram of the noise source must be supplied.

(4) Each type of noise source must be fitted with a 14-mm precision output connector. A 14-mm adapter is acceptable if it is securely attached to the existing coaxial connector on the mount.

Rectangular Waveguide Noise Sources:

(1) Effective noise temperature measurements are made on waveguide noise sources (usually a gas-discharge tube) under conditions of continuous, unmodulated operation.

(2) The direct current required for normal operation of the gas discharge tube should not exceed 200 mA but should be sufficient to prevent excessive plasma oscillation.

(3) Complete information on the operating current of the tube and a wiring diagram of the noise source must be supplied. In some cases it is necessary to request appropriate electrical connectors to be supplied with the unit for use during calibration.

(4) The gas-discharge tube should be secured in a terminated waveguide noise-tube mount.

References

[1] **Basic theory of waveguide junctions and introductory microwave network analysis,** D. M. Kerns and R. W. Beatty, Chapter in *International Series of Monographs on Electromagnetic Waves* **13,** 150 pages (Pergamon Press, Inc., New York, NY, 1967).

[2] **Measurement of effective temperatures in microwave noise sources,** J. S. Wells, W. C. Daywitt, and C. K. S. Miller, *IEEE Trans. Instrum. Meas.* **IX-13,** No. 1, 17-28 (Mar. 1964). (This reference describes the method of measurement and error analysis.)

[3] **Noise standards, measurements, and receiver noise definitions,** C. K. S. Miller, W. C. Daywitt, and M. G. Arthur, *IEEE Proc.* **55,** No. 6, 865-877 (June 1967). (This reference describes noise standards, basic principles of noise measurements, and concepts of noise factor and noise temperature.)

[4] **Considerations for the precise measurement of amplifier noise,** *Natl. Bur. Stand. (U.S.), Tech. Note 640,* 129 pages (Aug. 1973). (This technical note discusses the accuracy in measuring noise figure using accurate noise sources.)

F. Phase Shift

1. Special Phase Shift Measurement Services and Consultation

The specific phase shift services listed below are available on a limited basis depending on other demands and staff availability. Measurements not listed can be provided if sufficient advance notice is given. The cost of such services must be negotiated and will, in general, be higher than the established phase shift services. Consultation by telephone or written correspondence is suggested as indicated in the Appendix. Often a measurement technique can be suggested that will permit the customer to perform calibrations in-house with appropriate reference to other NBS-supported standards.

2. Coaxial Devices

Fixed and variable coaxial two ports are measured on the NBS modified Automatic Network Analyzer (ANA) over the frequency range 0.1 to 18 GHz. In addition, measurements can be performed with reference to a precision variable air line at 30 MHz.

Because of the specialized nature of coaxial phase shifting components, it is requested that prior discussions be held before submission of any devices to NBS.

Limits of Uncertainty

The limits of uncertainty stated are the sums of systematic, mismatch, and random errors. Their relative values are dependent upon the particular standard under calibration. The VSWR of the device and the quality of the connectors will contribute to the uncertainties of calibration.

Items to be calibrated must be fitted with connectors having a known plane of reference such as the sexless precision connectors, or Type N connectors meeting Mil C 39012.

General

The phase angle measured is $\psi+360\ n$, where n is an integer. The value of n is not determined.

Definitions

Characteristic insertion phase shift (phase change)—is the phase change of a wave incident upon the load before and after insertion of a two-port device between the generator and load of a stable nonreflecting system.

Characteristic phase shift difference (phase change)—is the phase change of a wave incident upon the load from an initial to a final condition (setting) of a two-port device between the generator and load of a stable nonreflecting system.

Note: The following conditions apply: (1) The frequency, the load impedance, and the generator characteristics (internal impedance and available power) have the same values before and after the device is inserted or changed; (2) the joining devices (connectors or adapters) belonging to the system all conform to a given set of standard specifications (the same specifications must be used by different laboratories if measurements are to agree precisely); (3) the nonreflecting conditions are to be obtained in uniform, standard sections of transmission line on the system sides of the connectors at the place of insertion; (4) this definition is not for phase shift in general, but for a particular phase shift which is characteristic of the device under measurement.

3. Waveguide Devices

In a rectangular waveguide the measurement services are limited to phase shift difference. Measurements are made on continuously variable waveguide phase shifters with the zero value of the scale as the normal reference position. Since 360 mechanical degrees of rotation represent 720 electrical degrees, attention should be given to the relationship between dial indication and actual mechanical position of the rotating vane assembly.

Measurements are performed for phase angle values from 0° to 720°.

Variable phase shifters should have a repeatability of dial setting better than ±0.5° and an input VSWR less than 1.4 at each waveguide port.

It is suggested that measurements requested be held to a minimum number of settings at a single band center frequency which should be sufficient to determine the characteristics of the device. We further recommend that previously calibrated units not be resubmitted unless tests performed by the user indicate a shift in values.

Limits of Uncertainty

The estimated limits of uncertainty range from ±0.1° to ±1.0° for input VSWR values of the phase shifter waveguide ports in the range 1.1 to 1.4.

Reference

[1] **Evaluation of a microwave phase measurement system,** D. A. Ellerbruch, *J. Res. Natl. Bur. Stand. (U.S.),* **69C** (Eng. and Instr.), No. 1, 55-65 (Jan.-Mar. 1965).

G. Power Measurements

Regular calibration services include thermistor-type bolometer units having a nominal resistance of either 100 or 200 Ω at a bias current between 3.5 and 15 mA and thermoelectric (TE) power sensor-power meter units.

Thermistor-type bolometer units have shown adequate stability over long periods of time (approx. 10 yr) and warrant long recalibration intervals. Two- or three-year recalibration intervals are recommended once the stability of a bolometer unit has been verified. Thermoelectric power sensor-power meter units must be linear with power level to within 0.02 dB/10 dB on 10 mW range. Measurement of the output of the internal power reference at NBS prior to calibration is required.

Assistance is available for applying published, technically valid measurement techniques in lieu of previously available calibration services for coaxial and waveguide calorimeters, power meters, and bolometer coupler units. The attainable limits of measurement uncertainty using these techniques are comparable to those of the previously available calibration services for these devices.

Reference

[1] **Accurate microwave high power measurements using a cascaded coupler method,** K. E. Bramall, *J. Res. Natl. Bur. Stand. (U.S.),* **75C** (Eng. and Instr.), Nos. 3 and 4, 181-186 (July-Dec. 1971).

Effective Efficiency, ηe

The effective efficiency is the ratio of the bolometrically substituted dc power in the bolometer unit to the cw rf/microwave power absorbed by the bolometer unit. The principal emphasis is on those calibrations and other tests requiring such accuracy as can be obtained only by direct comparison with NBS standards. However, in order to maintain efficient utilization of specialized equipment and skilled personnel, when workload permits NBS may calibrate devices requiring lesser accuracy but suitable for working standards in plant or laboratory. Also, upon request, special measurements may be made. Inquiries should describe clearly the measurement desired and indicate the scientific or economic basis for the requirement.

Calibration Factor—Bolometer Units, K_B

The calibration factor is the ratio of the bolometrically substituted dc power in the bolometer unit to the cw rf/microwave power incident upon the bolometer unit $K_B=\eta e(1-|\Gamma|^2)$.

Amplitude Reflection Coefficient, Γ

Amplitude reflection coefficient is the ratio of the reflected wave amplitude to the incident wave amplitude.

Effective efficiency and reflection coefficient are included in the Report of Calibration for all single frequency measurements. (For details see Appendix under Power Measurements, Electromagnetic, Single Frequency.)

Effective efficiency and reflection coefficient are included in the Report of Calibration for all multiple frequency broadband measurements. (For details, see Appendix under Power Measurements, Electromagnetic Multiple Frequency Broadband.)

Efficiency Factor—TE sensor-power meter units: Efficiency factor (mW/V) is the ratio of the power absorbed by the sensor head to the dc voltage at the recorder output of the meter on the 10 mW range. Reflection coefficient magnitudes at measured frequencies are included in the report of calibration.

The above services are restricted to the following conditions and equipment (except for special calibrations).

Power Level: 10 mW (nominal)

Bolometer Units and TE Power Sensor—Power Meter Units

Connector Types: Coaxial—type N to 18 GHz
7 mm precision to 18 GHz
(Measurements will be performed only in frequency bands appropriate to connector type.)
Waveguide:—WR15, and WR28 to WR284

(1) Single Frequency Measurements

Specify frequency for waveguide WR 15 (50.0-75.0 GHz) and WR28 to WR42

Specify frequency in range 0.1 to 10 MHz for special low frequency bolometer units. (Values for ηe and $|\Gamma|$ are calculated from voltage and resistance measurements. $\eta e=(P_{dc})/(P_{rf})$ where $P_{rf}=V^2/R_p$, where R_p is the parallel equivalent resistance and P_{dc} is the bolometrically substituted dc power in the bolometer.)

(2) Multiple Frequency Broadband Measurements

Schedule of Services

To improve service, reduce cost and "turnaround" time and facilitate planning, measurements will be conducted according to the following schedule. Purchase orders and devices should arrive at NBS/Boulder prior to the first day of the month in which calibration is desired.

Type N	Jan., Apr., June, Aug., Nov.
7 mm precision	Mar., Sept.
Waveguide	Feb., May, July, Oct., Dec.

Coaxial

100-100 MHz	10, 50, & 100 MHz
100-1000 MHz	100, 500, & 1000 MHz
10-1000 MHz	10, 50, 100, 500, & 1000 MHz

Note: Only bolometer units designed for low frequency operation will be calibrated below 100 MHz.

Coaxial

1-2 GHz	50 MHz intervals
2-4 GHz	100 MHz intervals
4-8 GHz	200 MHz intervals
8-12.4 GHz	200 MHz intervals
12.4, 12.75-18 GHz	250 MHz intervals

Waveguide

WR284	2.6-4.0 GHz	6 frequencies
WR187	4.0-5.8 GHz	100 MHz intervals
WR137	5.8-8.0 GHz	100 MHz intervals
WR112	7.0-10.0 GHz	200 MHz intervals
WR90	8.2-12.4 GHz	200 MHz intervals
WR75	10.0-15.0 GHz	250 MHz intervals
WR62	12.4-18.0 GHz	250 MHz intervals

Limits of Uncertainty

Effective efficiency and calibration factor: The estimated limits of uncertainty will vary from approximately ±0.5 to 2 percent depending on the frequency and the characteristics of the unit being calibrated such as connector type, reflection coefficient, and repeatability.

Reflection coefficient: The estimated limits of uncertainty are $\pm 0.005\sqrt{f}$(GHz).

(3) Rf and Microwave Coaxial Peak Pulse Power Meters and Power Meter-Directional Coupler Combinations

Services Available

(1) Input peak pulse power versus scale reading of terminating-type instruments.
(2) Input and/or output peak pulse power versus scale reading of feed-thru instruments.

Frequency range (GHz)	Peak power range (W)
0.3 to 0.5	0.001 to 2500
0.95 to 1.25	.001 to 5000
4.0 to 4.4	.001 to 2000

The uncertainties of these measurements are typically ±3 percent. The ±3 percent uncertainty is based on:

(a) ±1 percent on the cw power measurement (Reference)
(b) ±1 percent on cw-pulse power comparison circuits
(c) ±1 percent on the calibration of range-extending directional couplers

These errors are independent, and should be treated as such.

General

Calibrations are made with pulsed rf waves modulated by a baseband trapezoidal pulse. Limits of other basic parameters of the pulses are as follows:

Pulse duration range	0.5 to 10 μs
Pulse repetition rate range	100 to 1600 pps
Maximum duty factor	0.0033

Instruments submitted for calibration should have a nominal impedance of 50 Ω, and be fitted with Type N, BNC, HN, or 7 or 14-mm precision connectors. If other connectors are used, degradation of the above mentioned uncertainty limits could result.

H. Voltage Measurements

Services are available for two types of electromagnetic voltage measuring devices as follows:

1. Voltage Measurements of Thermal Voltage Converters (TVC's)

The TVC category also includes other devices using thermal detectors such as Rawson RF Voltmeters, Thermal Transfer Standards, RF Voltage Standards, and AC-DC Transfer Standards.

Services Available: rf-dc Difference

The rf-dc difference is defined as the percentage difference between the rf and dc output voltages required to produce the same thermocouple output, i.e..

$$\text{rf-dc difference} \quad (\%) = \left(\frac{V_{rf} - V_{dc}}{V_{dc}}\right) \times 100$$

Frequency (MHz)	rf voltage range (V)	Estimated limits of uncertainty* (±%)
0.03	0.1 to 200	0.05
.1	.1 to 200	.05
.3	.1 to 200	.05
1	.1 to 200	.05
3	.1 to 200	.1
10	.1 to 200	.1
30	.1 to 200	.2
100	.1 to 200	1.0

*No rf-dc differences greater than ±20 percent will be reported. This normally limits the calibrations to 100 MHz and below.

For high-frequency TVC's with a built-in "T" connector, the services available are:

Frequency (MHz)	rf voltage range (V)	Estimated limits of uncertainty (±%)
10, 30, 100	0.1 to 7.5	1
200, 300, 400		
500, 600, 700		
800, 900, 1000		

Calibrations having ±1 percent accuracy are performed only on the new high frequency thermal voltage converters with a "T" connector incorporated in the converter housing. The measurement reference plane is at the Type "N" male output connector. Other types of TVC's calibrated above 100 MHz will have accuracies of 3 to 5 percent.

General

Most converters have rf-dc differences within ±0.01 percent of zero at 1 MHz and below. All converters having previous calibration history that are submitted for recalibration should be evaluated at 1 MHz and results compared to prior data. If the difference is negligible, no further calibrations are usually necessary below 1 MHz.

Many years of experience in calibration of micropots and TVC's have shown that these are very stable devices even for periods of up to 10 years. Thus, in most cases, a 2-year or longer recalibration cycle is recommended. An exception might be the micropots which operate below 100 μV.

Assurance of device stability can be obtained by intercomparison of micropots or TVC's with others which are adjacent in voltage. For example, a 0.3 to 1 V TVC can be compared with a 1 to 3 V TVC at 1 V, etc.

2. Voltage Measurements of rf Micropotentiometers

Service Available: rf-dc Difference

The rf-dc difference is defined as the percentage difference between the rf and dc output voltages required to produce the same thermocouple output, with the resistive element terminated in 50 Ω.

Any frequency within band (MHz)	rf voltage range (μV)	Estimated* limits of uncertainty (±%)
0.05 to 100	1 to 100,000	2
100 to 500	1 to 100,000	3
500 to 900	1 to 100,000	5

*For rf-dc differences greater than ±20 percent, estimated limits of uncertainty are larger than those listed.

General

Rf micropotentiometers are usually calibrated at their nominal rated output voltages. Frequencies suggested for a normal calibration are 5, 100, 300, 400, 500, 700, and 900. For special calibrations to 1000 MHz see Appendix 4.9E.

Rf micropotentiometers having resistive elements greater than 10 mΩ, in combination with thermoelement housings between 5 and 100 mA, usually have rf-dc differences within ±1 percent of zero at 5 MHz. Since the rf-dc difference approaches zero below 5 MHz, calibrations at 50 kHz and 5 MHz would suffice to determine interpolated points of interest between 50 kHz and 5 MHz, with no appreciable loss of accuracy.

An rf-dc difference of about ±5 percent at 1 MHz usually results from a combination using a 1 mΩ element. Interpolation below 1 MHz is not recommended in this case.

I. Baseband Pulse Parameters

Pulse characteristics are important in a variety of applications. As a result NBS offers the following pulse measurement services.

1. Impulse Generator Spectrum Amplitude

In response to calibration needs from the electromagnetic interference (EMI) community, NBS has developed a measurement service to calibrate the broadband spectrum amplitude output from impulse generators. Such a generator can then be used as a transfer standard of broadband impulsive noise for field calibration of spectrum analyzers and field intensity meters. The NBS calibration service uses the time domain measurement/Fourier transformation computation (TD/FFT) method for calibration of impulse generators. A wideband (dc-18 GHz) sampling oscilloscope is used to measure the time domain waveform from the impulse generator. A dedicated minicomputer then computes the spectrum amplitude, $S(f)$, versus frequency using the fast Fourier transform (FFT).

Many of the limitations concerning the frequency range and spacing of the calibration service are related to the FFT. With an oscilloscope it is not possible to observe waveforms from $t=-\infty$ to $+\infty$. One can only observe a waveform within a limited time window. For this particular measurement service time windows of 10, 20, 50, 100, and 200 ns are available. Within the time window the sampling oscilloscope measures 1024 separate, uniformly spaced, values of the waveform. These sampled data are then transformed to the frequency domain using the FFT. Due to the mathematics of the FFT, the lowest frequency resulting from the computation is the reciprocal of the time window (i.e., 50 ns $\rightarrow$20 MHz). The other frequency components are harmonics of the fundamental (i.e., 20, 40, 60, 80 MHz . . .). The highest frequency component is $1/(2\ \Delta t)$, where Δt is the time domain sample spacing and $\Delta t = T/N$. T is the time window and N is the number of sampled data values in the time window. For the 50 ns window Δt is 48.8 ps and f_{max} is 10.24 GHz. Due to various accuracy considerations the time window is chosen such that at least 10 data points are obtained on the major feature of the impulse waveform. Fewer data points rapidly introduce significant errors in the computations. As an example an impulse of 500 ps duration would be measured over a 50 ns time window with a Δt of 48.8 ps and a resulting spectrum amplitude data table starting at 20 MHz. Another significant limitation on the choice of the time window is the requirement that no other spurious pulses occur outside of the window and that the waveform be completely relaxed and resting on the baseline at the beginning and end of the time window. If these criteria cannot be met then the generator is rejected for calibration.

Another major requirement is the necessity to trigger the sampling oscilloscope in advance of the impulse to be measured. As noted in the first reference in the next paragraph most impulse generators use a mercury switch and thus do not furnish a suitable trigger signal. For these generators a delay line triggering arrangement is used. A time window of 200 ns is the broadest that can be used with this arrangement. This sets the 5 MHz lower limit on the service capabilities given below. This limit can be extended to broader time windows and lower frequencies if the generator is an electronic generator with a suitable trigger pulse and adjustable delay.

Several techniques are available for measuring spectrum amplitude. For a summary see: J. R. Andrews, "Impulse generator spectrum amplitude measurement techniques," *IEEE Trans. Instrum. Meas.* **25**, No. 4, (Dec. 1976) pages 280 ff. For other details on spectrum amplitude measurements, see J. R. Andrews, M. G. Arthur, **Spectrum amplitude definition, generation and measurement,** *Natl. Bur. Stand. (U.S.), Tech. Note 694.*

Eighty percent of the impulse generators calibrated at NBS are of the mercury switch variety with an impulse duration of the order of 0.5 ns and adjustable amplitude. NBS impulse generator spectrum amplitude measurement service capabilities are as follows:

Parameter	Limits	Notes
Maximum impulse amplitude without attenuators	$\pm$400 mV	1, 2, 3
Maximum impulse amplitude with external attenuators	$\pm$1.2 mV	3,4
Spectrum amplitude	-15 dBμV/MHz$<[S(f)-S_0]<$ $+5$ dBμV/MHz	5, 6, 7
$S(f)$ uncertainty	Nominally $f\leqslant 1$ GHz, $\pm$0.6 dB 1 GHz$<f\leqslant 4$ GHz, $\pm$1.2 dB 4 GHz$<f\leqslant 6$ GHz, $\pm$2.0 dB	5, 6, 7 8 & 9
Frequency range	5 MHz to 6 GHz	5, 6, 7 & 10
Frequency spacing	$\Delta f=5,10,20,50$, or 100 MHz	5, 10
Frequency uncertainty	of the order of $\pm 1\%$	7
Load impedance	50.0 Ω	
Load impedance uncertainty	Nominally $\pm$0.1 Ω at dc VSWR $<$1.3 up to 6 GHz	8, 11
Trigger pulse magnitude	$>$100 mV	12
Trigger pulse transition time	$<$5 ns	12
Trigger to impulse delay	75 ns$<t_t<$100 ns	12
Trigger to impulse jitter	$<$20 ps	12

Notes

(1) The impulse generator is characterized by its impulse output waveform into 50 Ω of peak amplitude (V_{pk}), 50 percent level duration (τ), and low frequency spectrum amplitude ($S_0 \sim 2V_{pk}\tau$).

(2) Impulse generator with an adjustable amplitude impulse output will be calibrated with the generator adjusted to give a peak amplitude in the range of 200 to 400 mV.

(3) Impulse generators with fixed outputs greater than ±400 mV must have the impulse attenuated to the 200-400 mV level by 50 Ω wideband coaxial attenuators.

(4) Either customer supplied or NBS attenuators may be used.

(5) Depends upon actual generator characteristics.

(6) Data will not be given in the first spectrum null or at frequencies above. Typically 100 data points are supplied.

(7) Subject to revision.

(8) Only for impulse amplitudes less than ±400 mV.

(9) If external attenuators and/or a 6 dB tee and delay line are used then the uncertainty associated with the attenuator calibration is added to these values.

(10) Lower frequencies (<5 MHz) are available as a special test.

(11) Depends upon input impedance of external attenuators when used.

(12) If the impulse generator does not supply a trigger output or if the trigger output does not have the proper characteristics then a 6 dB tee and a delay line will be used to provide a suitable trigger pulse.

2. *Pulse Transition Duration*

Pulse transition duration (rise time) measurements for step function pulse generators and low pass filters are also available. Both measurements use an 18 GHz bandwidth, 20 ps transition time sampling oscilloscope to measure the pulse waveform. The observed waveform is computer processed to determine the transition duration. In the case of filters a 15 ps tunnel diode pulse generator is used as the source. For details on specific services, see the Appendix under pulse generator transition duration and low pass filter transition duration respectively.

3. *Wideband Attenuation or Gain*

Wideband attenuation or gain measurements on coaxial networks, using pulse techniques, provide data over a 100 kHz to 12.5 GHz frequency range, and 0 to 40 dB loss or gain range. This is accomplished by use of the NBS Time Domain Automatic Network Analyzer. It consists of a 20 ps transition time pulse generator, a 20 ps sampling oscilloscope and a minicomputer. Two waveforms are measured, one with the generator connected to the oscilloscope and the other with the unknown network inserted between the generator and the oscilloscope. The minicomputer provides the spectrum data for the two waveforms using the fast Fourier transform. The ratio of the two spectra is the attenuation or gain of the network. A wide variety of connectors can be accommodated.

4. *Pulse Time Delay*

Pulse time delay is also measured using the same generator and oscilloscope. A coaxial trombone line stretcher is connected in the trigger circuit between the generator and oscilloscope. The length of the line stretcher is adjusted to center on the 50 percent point on the pulse leading edge. The change in length of the line stretcher for this adjustment with the unknown alternately inserted and removed from the signal channel between the generator and oscilloscope is used to compute time delay. For details on services available, see the Appendix under Attenuation, Phase Shift, and Power, respectively. For information on Pulsed rf Power measurements, see section V.G.

J. Electromagnetic Interference Measurements

An electromagnetic interference (EMI) program in process is currently developing measurement methods and instrumentation for the evaluation of susceptibility and emission of devices, components, subsystems, and small systems. Large subsystem and system measurements will be addressed on an individual case basis. The objective is to achieve repeatable (to <0.5 dB) and accurate EMI measurements, typically exceeding the accuracies called for in Mil. Standards 461 and 462.

This program is also directed toward developing measurement methods and instrumentation for the evaluation of the electromagnetic (EM) environment primarily to assess the electric and magnetic fields in the near-field area of intentional or unintentional emitters to establish the EM

ambient environment. Where necessary methods and instrumentation for far-field measurements will be developed. This work will also concern itself with display methods and statistical measures for EM ambient environment evaluation.

This program also assists the electromagnetics biohazards community by developing techniques and instrumentation they might use in measuring EM fields. The measurements needed to support this area are very nearly the same as those for EMI; therefore, only minor changes to EMI measurements are needed for biohazard measurement applications.

NBS does not provide routine measurement services for electromagnetic interference, although a limited number of measurements are available by special arrangements. Consulting and advisory services are available.

CHAPTER VI

VI. Time and Frequency

Direct inquiries to the Time and Frequency Division in Boulder (address and phone number as stated in the Appendix).

The National Bureau of Standards develops and maintains the NBS standards of frequency and time. It disseminates frequency and time from these standards via radio broadcasts from Colorado and Hawaii and experimentally from satellites. In addition, frequency and time calibration services using network television and other non-NBS broadcasts are available. A limited service of direct comparison of a customer's signal source (precision oscillator) or clock with the NBS frequency and time standard is also provided as well as direct noise measurements of precision oscillators. The current basic frequency standards operate at 5 MHz, however, NBS' frequency technology permits comparisons ranging from *several hertz to about 900 THz.* Consultation on atomic clocks and frequency standards, precision oscillators, infrared and optical coherent sources, stabilization and intercomparison and dissemination methods is available. NBS conducts scientific comparisons with the frequency and time standards of other nations and NBS standards provide data for the development of International Atomic Time (TAI).

A. NBS Frequency Standard

The General Conference of Weights and Measures, at its 13th General Meeting (1967), adopted the following definition for the second in the International System (SI) of Units.

"The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the atom of cesium 133."

NBS maintains equipment, known as the NBS Frequency and Time Standard (NBS FTS) for realizing this definition of the second with an accuracy of 1×10^{-13}.

B. NBS Time and Frequency Dissemination Services

Services available from radio broadcasting stations and time and frequency calibration services using network television and the experimental GOES satellite time code are detailed in NBS Special Publication 432 (Rev. 1979). This publication is revised from time to time as changes are introduced.

For experimental services available from satellites see:

[1] **Dissemination of time and frequency by satellite,** R. L. Easton, L. C. Fisher, D. W. Hanson, H. W. Hellwig, and L. J. Rueger, *Proc. IEEE* **64**, No. 10, 1482-1493 (Oct. 1976).

[2] **NBS time to the Western hemisphere,** D. W. Hanson, D. D. Davis, and J. V. Cateora, *Radio Science* **14,** No. 4, 731-740 (July-Aug. 1974).

[3] **Time recovery measurements using operational GOES and TRANSIT satellites,** R. E. Beehler et al., *Proc. 11th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting,* 283-315 (Nov. 1979).

C. Direct Signal Source Calibration Services

NBS does not routinely calibrate signal sources or clocks; however, upon request special measurements may be made. Special requests will be considered for oscillator frequency and noise measurements. Inquiries should describe clearly the measurement desired and the importance or significance of making a direct comparison with the NBS FTS. The signal source to be measured should have a power output of 20 mW (into a matched load) or greater. For details on nominal

frequencies at which calibrations can be readily done, depending on workload, see the Appendix under the heading "Frequency Measurements."

For the current primary cesium standard NBS-6, the accuracy, $\Delta f/f$ has been determined to be $\pm 8 \times 10^{-14}$, which includes one sigma estimates of the possible random errors in frequency associated with the measurement of various parameters of the standard. The stability of the standard becomes a factor in measuring stability of other precision oscillators. The contribution to the overall measurement uncertainty due to the instability imposed by fluctuations of NBS-6 when paired with a similar oscillator depends on measurement averaging time and can be expressed as

$$\sigma_y(\tau) = 1 \times 10^{-12} \ \tau^{-1/2}$$

where $\sigma_y(\tau)$ is the two-sample deviation of the frequency fluctuations and τ = the length of the frequency comparison in seconds. The measurement limit is 10^{-14}. Noise measurements are expressed in the time domain by measurements of the two-sample deviation $\sigma_y(\tau)$ or in the frequency domain by measurement of phase noise $S_\phi(f)$. For specific details on the noise services available see the Appendix under the heading "Oscillator Noise Measurements."

In addition, time measurement services are available for time pulses at the rate of one pulse per second. See the Appendix under the heading "Time Pulses."

References

[1] **Clocks and measurements of time and frequency,** H. Hellwig, *Proc. 1976 WESCON,* Session 32, pp. 1-4 (Institute of Electrical and Electronics Engineers, New York, NY, Sept. 1976).

[2] **The National Bureau of Standards Atomic Time Scale: Generation, stability, accuracy and accessibility,** D. W. Allan, J. E. Gray, and H. E. Machlan, *Natl. Bur. Stand. (U.S.), Monogr. 140,* Chap. 9, 205-231 (May 1974).

[3] **Design principles and characteristics of frequency and time standards,** H. Hellwig, *IEEE Trans. Nucl. Sci.* **NS-23,** No. 6, 1629-1635 (Dec. 1976).

[4] **Results on limitations in primary cesium standard operation,** D. J. Wineland, D. W. Allan, D. J. Glaze, H. W. Hellwig, and S. Jarvis, Jr., *IEEE Trans. Instrum. Meas.* **IM-25,** No. 4, 453-458 (Dec. 1976).

CHAPTER VII

VII. Thermodynamic Quantities

The Thermodynamic Quantities program provides measurement services in the areas of thermometry, pressure and vacuum, humidity, and cryogenic measurements as described in the sections which follow.

A. Thermometry

The National Bureau of Standards employs the International Practical Temperature Scale of 1968 and the 1976 Provisional 0.5 K to 30 K Temperature Scale as the basis for its calibration activities in thermometry. However, the NBS temperature calibrations are not limited to those which are specified in these scales; non-"standard" sensors may be calibrated, and calibrations beyond the limits of the IPTS-68 and EPT-76 may also be provided. In all cases, however, great care is taken to make such calibrations consistent with the IPTS-68 and EPT-76.

The platinum resistance thermometer and the platinum-10 percent rhodium versus platinum thermocouple are the specified interpolating instruments in the IPTS for the range 13.81 K to 630.74 °C and 630.74 to 1064.43 °C, respectively. NBS offers calibrations for both of these instruments throughout their respective ranges. In addition to these calibrations, NBS routinely provides many other calibration services. These include calibrations of:

° many liquid-in-glass laboratory thermometers

° thermocouple thermometers of many types, from cryogenic temperatures to 1750 °C

° germanium resistance thermometers and other thermometers used in realizing the EPT-76.

Moreover, in collaboration with its thermometry research and development staff, NBS provides special at-cost calibrations of thermistor thermometers, of certain industrial types of resistance thermometers, and of a variety of thermometry systems.

Whenever there exists a desire to calibrate contact thermometry equipment over the temperature range 0.1 to 2000 K, the user is invited to contact the temperature calibration staff as indicated in the Appendix.

1. Laboratory Thermometers

Kinds of Thermometers Accepted for Calibration

Thermometers belonging to the large and varied group which may be classed as laboratory or "chemical" thermometers are regularly accepted. Many of these are of the liquid-in-glass type with either solid-stem or enclosed scale. Other acceptable types include such special-purpose thermometers as Beckmann and calorimeter thermometers.

Ordinary household or meteorological thermometers will not, in general, be accepted unless the scale is graduated on the glass stem itself and the thermometer can be readily detached from its mounting for insertion in a testing bath.

Every thermometer submitted must be uniquely identified by a serial number and must pass a preliminary examination for fineness and uniformity of graduation; for cleanliness of the mercury and capillary bore; for freedom from moisture, gas bubbles, and cracks in the glass; for adequacy or omission of gas filling where needed; for insufficient annealing; and for misnumbered graduations. When these or other serious defects are found, the thermometer is returned untested.

Shipping Instructions

Shipping charges, both to and from the Bureau, must be assumed by the applicant. Return shipments are made by the Bureau in accordance with its judgment of the best method of shipping unless specific instructions are received. Such instructions should be supplied at the time that arrangements are being made for the test. If a test number has been assigned prior to the shipment, this number should appear on the shipping container. If a test number has not been assigned at this time, a purchase order, or letter should be sent under separate cover. In either case, the shipment should include a packing list.

All possible care will be taken in handling thermometers at the Bureau, but the risk of damage either in shipment or in testing must be assumed by the applicant. The applicant should consider the nature of the equipment shipped and pack it accordingly, with appropriate labeling. Attention is called to the availability of security express in shipping thermometers.

Details of the procedures used in calibrating laboratory thermometers may be found in NBS Monograph 150, "Liquid-in-Glass Thermometry," U.S. Government Printing Office, Washington, DC 20402, 1976.

2. Thermocouples, Thermocouple Materials, and Pyrometer Indicators

Methods of Calibration

In order to calibrate thermocouples to yield temperature versus emf relationship on the International Practical Temperature Scale, they must be so calibrated that their indications agree with those of the standard platinum resistance thermometer in the range –259.34 to 630.74 °C, the standard platinum-10 percent rhodium versus platinum thermocouple in the range 630.74 to 1064.43 °C, and the optical pyrometer above 1064.43 °C.

The temperature-emf relationship of a homogeneous thermocouple is a definite physical property and, therefore, does not depend upon the details of the apparatus or method employed in determining this relation. Consequently, there are numerous methods of calibrating thermocouples, the choice of which depends upon the type of thermocouple, temperature range, accuracy required, size of wires, apparatus available, and personal preference.

Services Offered

A listing of the thermocouple calibration services is given in the Appendix under the title "Thermocouples."

° Only the bare wires are required to perform the thermocouple calibrations.

' It is preferable not to send insulating and protecting tubes as the rate of breakage of these in shipment is high.

° If the thermocouple is furnished mounted (as in a protection tube assembly) a nominal charge will be made for dismantling the mounting and the various parts will be returned to the sender without reassembling them.

° Thermocouple length requirements listed in the Appendix are exclusive of lead wire. Lead wire need not be sent with thermocouples.

° All thermocouple calibration data furnished in reports will be on the basis of a reference junction temperature of 0 °C or 32 °F. The calibration results will be given in degrees C or F, as requested by the customer.

° The calibration or test of a thermocouple will not be undertaken if, in our opinion, it will not yield the specified accuracy or if it possesses such unusual characteristics as to prevent the carrying out of the calibration or test at a reasonable cost. Only unused base-metal thermocouples and thermocouple materials will be accepted for test.

° Inquiries concerning other types of thermocouples, e.g., tungsten-rhenium types, are welcome. NBS will attempt, whenever possible, to meet reasonable calibration requests. The fees for the work accepted will be based on the actual costs incurred. The technical staff should make the inquiry directly with information on the nature of the thermocouple and the type of calibration required so that services that are needed can be determined expeditiously.

3. Resistance Thermometers

The National Bureau of Standards offers calibrations of the standard platinum resistance thermometers which are specified for use as interpolation instruments in the text of the International Practical Temperature Scale of 1968 as amended 1975 (see the journal Metrologia, Vol. 12, pp. 7-17, 1976). In addition, less-precise resistance thermometers and thermistor thermometers are calibrated on the International Practical Temperature Scale, but with correspondingly reduced precision limits.

Standard Platinum Resistance Thermometers

To qualify for testing, either long-stem or capsule platinum resistance thermometers must meet several conditions:

- They must reasonably be expected to meet the requirements of the IPTS-68 for a standard interpolating instrument (i.e., a four lead resistor of high-purity platinum hermetically sealed in a protecting tube).
- They must be compatible with the NBS highest-precision calibration equipment (see the Appendix for further information and contact point).

The user may choose any of several types of calibration, as listed in the Appendix. He may also specify the form of the resulting calibration, $R(t)$, $[R(t)/R(O)]$, or $[R(t)-R(O)]$ versus temperatures based on the IPTS-68.

A minimum charge (see Appendix) is made on all standard platinum thermometers received. This charge will cover, in part, the cost of receiving and returning thermometers which, for some reason, are found to be unsuitable for test.

It is very important that, insofar as possible, resistance thermometers be protected from any mechanical shock which will alter their calibration. To be shipped, the thermometer must be softly supported within a case but not be free to rattle. This necessitates the use of packing material that does not become compacted. The thermometer case should in turn be softly packed inside a shipping container. The outside shipping container must be sufficiently rigid and strong not to appreciably deform under the treatment usually given by shippers. Styrofoam is not sufficiently rigid to be used as an outside container. Thermometers will not be returned in containers which are obviously unsuitable, such as those closed by nailing. Suitable containers will be provided, for a fee, when thermometer shipping container is not satisfactory for re-use.

"Non-Standard" Resistance Thermometers, Thermistors, and Other Thermometers

Industrial and laboratory-grade resistance thermometers which are not suitable for work at the highest precision may be calibrated also. In this case, the calibration will be referred to the IPTS-68 or the EPT-76, but the measurement precision and the equipment to be used will be appropriate to the quality of the sensor. Some thermometers may require a stability test before calibration.

These comments apply, as well, to thermistor thermometers, quartz thermometers, and other temperature sensors. These instruments may be offered for calibration on an "At Cost" basis. Special requirements for testing should be discussed with the NBS staff indicated in the Appendix.

4. Thermometer Systems

The National Bureau of Standards offers a service of analysis and calibration of thermometry systems, including sensors, reference baths, data loggers, and the like on an "At Cost" basis. This testing should be discussed with the appropriate NBS staff member well in advance of need, since it generally involves a complex relationship of the laboratory environment to the several component parts of the measurement apparatus.

5. Training

Twice a year, in spring and fall, Precision Thermometry Seminars are held at NBS. These seminars include 2 days of instruction and laboratory practice in platinum resistance thermometry,

and 1 day each for thermocouple thermometry, liquid-in-glass thermometry, and thermistor and temperature scale instruction and tours. The instruction is given by the NBS temperature calibration staff, and hands-on laboratory experience is included.

6. Radiation Thermometry

High precision monochromatic visual and automatic optical pyrometers are calibrated in the temperature range 800 °C to 4200 °C. Uncertainties in routine testing vary from ±3° at 1064 °C, to ±8° at 2800 °C, to ±30° at 4200 °C.

Ribbon filament lamps are calibrated using the NBS photoelectric pyrometer, and reports of brightness temperature at 655 nanometers versus direct current are issued. Uncertainties in routine testing vary from ±1.5° at 1064 °C to ±3° at 2300 °C.

References

[1] **The international practical temperature scale of 1968,** amended edition of 1975, *Metrologia* **12,** 7-17 (1976).

[2] **The 1976 provisional 0.5 K to 30 K temperature scale,** *Metrologia* **15,** 65-68 (1979).

[3] **Platinum resistance thermometry,** J. L. Riddle, G. T. Furukawa, and H. H. Plumb, *Natl. Bur. Stand. (U.S.), Monogr. 126* (Apr. 1973).

[4] **Thermocouple reference tables based on the IPTS-68,** *Natl. Bur. Stand. (U.S.), Monogr. 125* (1973).

[5] **Manual on the use of thermocouples in temperature measurement,** *ASTM Special Publication 470B.*

[6] **Liquid-in-glass thermometry,** J. A. Wise, *Natl. Bur. Stand. (U.S.), Monogr. 150* (Jan. 1976).

[7] **High-accuracy spectral radiance calibration of tungsten-strip lamps,** H. J. Kostkowski, D. E. Erminy, and A. T. Hattenburg, *Advances in Geophysics* **14,** 111-127 (1970).

[8] **The International Practical Temperature Scale of 1968,** *Metrologia* **5,** 35-44 (1969).

[9] **Theory and methods of optical pyrometry,** H. J. Kostkowski and R. D. Lee, *Natl. Bur. Stand. (U.S.), Monogr. 41* (Mar. 1962).

[10] **The NBS photoelectric pyrometer and its use in realizing the International Practical Temperature Scale above 1063 °C,** R. D. Lee, *Metrologia* **2,** No. 4, 150-162 (Oct. 1966).

[11] **Vacuum tungsten strip lamps with improved stability as radiance temperature,** T. J Quinn and R. D. Lee, *5th Symposium on Temperature, 1971, Instrument Soc. Am.,* p. 395-411.

B. Pressure and Vacuum Measurements

The National Bureau of Standards develops and maintains primary and secondary standards of pressure and provides calibration services for a wide variety of instruments against these standards. These services are supplemented by extensive consultations, training of industrial personnel, measurement assurance programs, evaluation of the performance of transfer standards, special tests and services, and research and development sponsored by industrial organizations or government agencies.

1. Piston Gages

The effective area and the pressure coefficient of piston gages are determined by comparison with NBS standards. A detailed report containing all the data taken and giving a full account of the numerical evaluation of the data is issued for each gage calibrated. If customer weights are not available, NBS owned weights can be used. The mass of small parts, such as pistons and small weight tables, can be determined as part of the calibration service. The mass of larger weights must be known before they are used for the piston gage calibration. Bases for some types of piston gages are available at NBS. In these cases only the piston cylinder assembly needs to be shipped to NBS.

2. Controlled Clearance Piston Gages

The effective area, the pressure coefficient of the area, and the jacket pressure coefficients are determined. A detailed report containing all the data taken and giving a full account of the

numerical evaluation of the data is issued for each controlled clearance piston gage calibrated. Since these calibrations are very time-consuming, NBS should be contacted in advance for scheduling.

3. Barometers

Mercurial barometers in which both menisci are observable are calibrated by comparison with a standard mercury manometer or a suitable transfer standard. A table of corrections to be applied to the barometer readings is issued.

4. Manometers

Mercury manometers in which both menisci are observable are calibrated by comparison with a standard manometer or a piston gage transfer standard. A table of corrections to be applied to the manometer readings is issued.

5. Pressure Gages

Indicating pressure gages with aneroids, bourdon tubes or other transducing elements are calibrated against suitable standards. A variety of gases or liquids can be used as pressure transmitting fluids. Gage, absolute or differential pressures can be applied. A table of corrections to be applied to the indicated pressure is issued.

6. Pressure Transducers

Absolute, differential, or gage pressure transducers are calibrated against suitable standards using a variety of liquids or gases as pressure transmitting fluids. Either the transducer only or the transducer with the associated instrumentation can be calibrated. The results are generally expressed as a polynomial in the indicated pressure. A detailed report containing the data taken and giving a full account of the numerical evaluation of the data is issued.

7. Vacuum Gages

Low and medium vacuum gages are calibrated by comparison with mercury or oil manometers, or with suitable transfer standards. Various gases such as N_2, H_2, He, and Ar can be used as the pressure transmitting medium. The results are generally expressed as a polynomial in the indicated pressure. High vacuum gages are calibrated between 1 and 10^{-4} Pa (10^{-2} and 10^{-6} Torr). In all cases a detailed report containing the data taken and giving a full account of the numerical evaluation of the data is issued.

8. Training

Training courses on pressure measurements with piston gages are held several times a year at NBS. These and other courses are also held upon request at other locations. These courses help to acquaint users of pressure standards and transfer standards with methods used at NBS and with the interpretation of calibration reports. Particular attention is paid to the assessment of uncertainties and the propagation of errors in the calibration chain.

9. Miscellaneous Tests and Services

Research and development projects in pressure and vacuum are sometimes carried out for industrial associations and government agencies. Upon request, subject to available resource constraints, NBS may provide measurement assurance services, assist in the investigation of accidents, assess the measurement capabilities of other laboratories, or provide consultation on pressure and vacuum measurements.

References

[1] **Pressure measurements and services at NBS,** P. L. M. Heydemann, presented at the Fluid Power Testing Symposium, Milwaukee, WI (1976). Available from NBS at the address listed in the Appendix.

[2] **Piston gages,** P. L. M. Heydemann and B. E. Welch, Chapter 4 in *Experimental Thermodynamics, Vol. II. Experimental Thermodynamics of Non-Reacting Fluids,* B. Le Neindre and B. Vodar, Eds., Part 3, pp. 147-202 (Butterworth and Co., London, England, 1975).

[3] **Ultrasonic manometers for low and medium vacua under development at NBS,** P. L. M. Heydemann, C. R. Tilford, and R. W. Hyland, *J. Vac. Sci. Technol.* **14,** 597 (1977).

[4] **Ultrasonic and dilatometric measurement at very high pressures,** P. L. M. Heydemann and J. C. Houck, *Natl. Bur. Stand. (U.S.), Spec. Publ. 326,* pp. 11-22 (Mar. 1971).

[5] **NBS pressure transducer characterization service,** V. E. Bean. Available from NBS at the address listed in the Appendix.

[6] **The National Measurement System for pressure,** P. L. M. Heydemann, *NBSIR 75-931,* 42 pages (Sept. 1976). Order from NTIS as PB261030.

[7] **Nitrogen sensitivities of a sample of commercial hot cathode ionization gage tubes,** C. H. Tilford, *J. Vac. Sci. Technol.* **18,** 994 (1981).

C. Humidity Measurements

The National Bureau of Standards provides calibration services for a wide variety of humidity-measuring instruments. Calibrations are performed by subjecting the instrument under test to atmospheres of known moisture content produced by the NBS two-pressure humidity generator.

1. Dew-Point Hygrometers

Dew-point hygrometers can be calibrated over the dew/frost-point range of 80 to –80 °C.

2. Electric Hygrometers

Hygrometers classified under this category are sensors which sorb water vapor as a function of relative humidity and associated with this sorption is a corresponding change in an electrical parameter (i.e., resistance, capacitance). The range of calibration is 3 to 98 percent RH over the temperature range –55 to 80 °C.

3. Psychrometers

A limited number of types of wet-dry bulb hygrometers (aspirated psychrometers) can be calibrated at the National Bureau of Standards. The staff of the Humidity Group should be consulted for the special features of the psychrometer which are necessary before the instrument can be calibrated at NBS.

4. Coulometric Hygrometers

Coulometric hygrometers are devices which electrolyze the water into gaseous oxygen and hydrogen by the application of a voltage in excess of the thermodynamic decomposition voltage and measure this electrolysis current. The range of calibration is 1 to 31,000 ppm by volume.

5. Pneumatic Bridge Hygrometer

Pneumatic bridge hygrometers are instruments which measure the variation of pressure drop across two combinations of nozzles, operating at critical flow, with a desiccant between one pair of nozzles. The range of calibration in mixing ratios, (gram water vapor/gram dry air), is 0.0005 to 0.015.

References

The following references are available from NBS at the address shown in the Appendix under "Humidity Measurements."

[1] **The NBS standard hygrometer,** A. Wexler and R. W. Hyland, *Natl. Bur. Stand. (U.S.), Monogr. 73,* 35 pages (May 1964).

[2] **The NBS two-pressure humidity generator, Mark 2,** S. Hasegawa and J. W. Little, *J. Res. Natl. Bur. Stand. (U.S.),* **81A** (Phys. and Chem.), No. 1, 81-88 (Jan.-Feb. 1977).
[3] **Vapor pressure formulation for water in range 0 to 100 °C. A revision,** A. Wexler, *J. Res. Natl. Bur. Stand. (U.S.),* **80A** (Phys. and Chem.), Nos. 5 and 6, 775-785 (Sept.-Dec. 1976).
[4] **Vapor pressure formulation for ice,** A. Wexler, *J. Res. Natl. Bur. Stand. (U.S.),* **81A** (Phys. and Chem.), No. 1, 5-20 (Jan.-Feb. 1977).
[5] **A correlation for the second interaction virial coefficients and enhancement factors for moist air,** R. W. Hyland, *J. Res. Natl. Bur. Stand. (U.S.),* **79A** (Phys. and Chem.), No. 4, 551-560 (July-Aug. 1975).

D. Cryogenic Measurements

The National Bureau of Standards provides consulting and advisory services in selected areas of cryogenics including properties of solids and fluids, cryogenic flow measurements, density measurements, and liquefied natural gas. Limited services are provided for cryogenic liquid flow and a static liquid density reference system is maintained. The primary aim of both systems is the establishment and calibration of transfer standards.

1. Cryogenic Flow Measurements

Mass flow measurements are performed with a gravimetric system using liquid nitrogen or liquid argon with flow rates of 76 to 757 liters/minute.

2. Density Reference System

A static density reference system is maintained which can compare liquid density transducers against a gravimetric balance. Measurements are performed in liquid methane and liquefied natural gas.

References

[1] **Cryogenic flow research facility provisional accuracy statement,** J. W. Dean, J. A. Brennan, D. B. Mann, and C. H. Kneebone, *Natl. Bur. Stand. (U.S.), Tech. Note 606,* 40 pages (July 1971).
[2] **Cryogenic fluids density reference system: Provisional accuracy statement (1980),** J. D. Siegwarth and J. K. LaBrecque, *Natl. Bur. Stand. (U.S.), Tech. Note 1041,* 60 pages (Apr. 1981).
[3] **NBS-CGA cryogenic flow measurement program,** J. A. Brennan, R. W. Stokes, C. H. Kneebone, and D. B. Mann, (Proc. ISA International Instrumentation Automation Conf. and Exhibit, New York, NY, Oct. 28-31, 1974), Paper in *Advances in Instrumentation* **29**, 612-1/612-13 (Instrument Society of America, Pittsburgh, PA, 1974).
[4] **Progress report on cryogenic flowmetering at the National Bureau of Standards,** J. A. Brennan, J. F. LaBrecque, and C. H. Kneebone, *Proc. 1st Biennial Symp. Instrumentation in the Cryogenic Industry, Houston, TX, Oct. 11-14, 1976,* **1,** 621-1/621-16 (Instrument Society of America, Pittsburgh, PA, 1976).
[5] **Cryogenic liquid-measuring devices, National Code on Specifications, Tolerances, and other technical requirements,** *Natl. Bur. Stand. (U.S.), Handbook 44.*
[6] **An evaluation of commercial densimeters for use in LNG,** J. D. Siegwarth, J. F. LaBrecque, and B. A. Younglove, *Natl. Bur. Stand. (U.S.), Tech. Note 698* (1977).
[7] **LNG density determination** D. E. Diller, *Hydrocarbon Process* **56,** No. 4, 142-144 (Apr. 1977).
[8] **LNG materials and fluids—A user's manual of property data in graphic format, 1st Edition,** D. B. Mann, ed., CDC $35.00; Suppl. 1, D. E. Diller, ed., CDC $15.00; Suppl. 2, N. A. Olien, ed. (1980) CDC $15.00.

CHAPTER VIII

VIII. Optical Measurements

A. Radiometry and Photometry

Calibrations and measurement services are offered in the optical radiation region of the electromagnetic spectrum for the basic properties of spectral radiance, spectral irradiance, detector spectral response, luminous intensity, luminous flux, and color temperature. The optical radiation region is that part of the spectrum using similar measurement techniques that extends from the vacuum ultraviolet (about 140 nm) through the visible to the infrared (approximately 25000 nm). Calibrations are offered as fixed fee items, listed in the Appendix, and require only a purchase order identifying the item number. Details of the calibration procedure and a summary of the documentation of the uncertainties are provided in each calibration report. The listed calibrations are performed under pre-determined conditions and are, therefore, restricted as to lamp type, measuring geometry, wavelength points, etc. Requests for departure from these conditions will be considered on a case-by-case basis. If such a request is accepted by NBS, fees are charged on an actual-cost basis, with an estimate of cost, delivery time, and uncertainty being provided after receipt of a description of the desired test, and before actual work commences. The request for unlisted measurement services should include the following information:

(1) Detailed description of desired calibration
(2) Uncertainty required (SI units, NBS standards)
(3) Manner in which the calibrated device will be used
(4) The consequences of this calibration not being provided by NBS.

1. Radiometric Standards

(a) Special Radiance Standard, Ribbon Filament Lamp (30A/T24/13).

Lamps of this type are calibrated at 33 wavelengths from 225 to 2400 nm, for a target area 0.6 mm wide by 0.8 mm high, and at a radiance temperature of about 2675 K at 225 nm, 2495 K at 650 nm, 2415 K at 800 nm and 1620 K at 2400 nm, with approximate uncertainties relative to SI units of 3 percent at 225 nm, 1 percent at 650 and 800 nm, and 0.5 percent at 2400 nm. The lamp requires about 40 A dc at 7 V. An interpolation formula allows calculation at all wavelengths except in regions of absorption bands. The lamp is normally provided by NBS[1].

References

[1] **High-accuracy spectral radiance calibration of tungsten-strip lamps,** H. J. Kostkowski, D. E. Erminy, and A. T. Hattenburg, *Advances in Geophysics* **14,** p. 111-127 (1970).
[2] **The International Practical Temperature Scale of 1968,** *Metrologia* **5,** p. 35-44 (1969).
[3] **Corrections in optical pyrometry and photometry for the refractive index of air,** W. R. Blevin, *Metrologia* **8,** p. 146-147 (1972).

(b) Spectral radiance standard for vacuum ultraviolet, argon mini-arc.

The spectral radiance of argon mini-arc radiation sources is determined to within an uncertainty of less than 7 percent over the wavelength range 140-330 nm and 20 percent over the wavelength range 115-140 nm. The calibrated area of the 4 mm diameter radiation source is the central 0.3 mm diameter region. Typical values of the spectral radiance are: at 250 nm, $L_\lambda = 30$ mW $cm^{-2}nm^{-1}sr^{-1}$; at 150 nm, $L_\lambda = 3$ mW $cm^{-2}nm^{-1}sr^{-1}$. The transmission of the demountable lamp window and that of an additional MgF_2 window are determined individually so that the user may check periodically for possible long term variations.

(c) Spectral radiance standard for vacuum ultraviolet, deuterium lamps.

The spectral radiance of low pressure deuterium arc lamps is determined to within an uncertainty of less than 7 percent over the wavelength range 165-350 nm in 10 nm intervals. The calibrated area of the radiation source is the central 0.3 mm diameter region. The lamp is normally supplied by the customer.

(d) Spectral irradiance standard, quartz-halogen 1000 watt type FEL lamp.

The lamp is calibrated at 26 wavelengths from 250 to 1600 nm, at a distance of 50 cm, and at a spectral irradiance of about 0.2 W/cm^3 at 250 nm, 220 W/cm^3 at 900 nm and 115 W/cm^3 at 1600 nm, with approximate uncertainties relative to SI units of 2.5 percent at 250 nm, 1 percent at 650 nm, and 1 percent at 1600 nm. The lamp is normally supplied by NBS, and requires about 8 A dc at 110 V. An interpolation formula allows calculation of the value at any wavelength except in regions of absorption bands.

Reference

[1] **The 1973 NBS scale of spectral irradiance,** R. D. Saunders and J. B. Shumaker, *Natl. Bur. Stand. (U.S.), Tech. Note 594-13* (U.S. Government Printing Office, Washington, DC, 1977).

(e) Spectral irradiance standard, deuterium lamp.

The deuterium spectral irradiance lamp standard is intended for use from 200 nm to 250 nm, a region where the 1000 watt quartz-halogen tungsten filament type FEL lamp gives very little power. The spectral irradiance of the deuterium lamp is approximately the same at 260 nm as the irradiance of the FEL lamp. The spectral irradiance increases toward shorter wavelengths, and decreases rapidly toward longer wavelengths. Therefore, for wavelengths greater than 250 nm, the FEL type lamp is recommended because of its higher, more stable signal, and improved accuracy.

The deuterium lamp is calibrated at 16 wavelengths from 200 to 350 nm, at a distance of 50 cm, at a spectral irradiance of about 0.5 W/cm^3 at 200 nm, 0.2 W/cm^3 at 250 nm, and 0.06 W/cm^3 at 350 nm. The approximate uncertainty relative to SI units is 6 percent at 200 nm and 3 percent at 250 nm. The approximate uncertainty in relative spectral distribution is 3 percent. It is strongly recommended that the deuterium standards be compared to an FEL tungsten standard over the range 250 to 300 nm each time the D_2 is lighted to take advantage of the accuracy of the relative spectral distribution. The lamp is normally supplied by NBS. It should be operated in series with a ballast resistor with power from a regulated supply operating at 500 V D.C. and 300 mA.

(f) Spectral irradiance standard for the vacuum ultraviolet deuterium lamp.

The lamp is calibrated at 10 wavelengths from 165 to 200 nm, at a distance of 50 cm, at a spectral irradiance of about 0.5 W/cm^3 at 165 nm, 0.3 W/cm^3 at 170 nm, and 0.5 W/cm^3 at 200 nm. The approximate uncertainty relative to SI units is estimated to be less than 10 percent. The lamp is normally supplied by NBS and requires 300 mA at about 100 V.

(g) Spectral irradiance standard argon mini-arc.

An argon mini-arc lamp supplied by the customer is calibrated for spectral irradiance at 10 nm intervals in the wavelength region 140 nm-300 nm. Absolute values are obtained by comparison of the radiative output with laboratory standards of both spectral irradiance and spectral radiance. The spectral irradiance measurement is made at a distance of 50 cm from the field stop. Uncertainties are estimated to be less than ± 10 percent in the wavelength region 140-200 nm and within ± 5 percent in the wavelength region 200-330 nm. A measurement of the spectral transmission of the lamp window is included in order that the calibration be independent of possible window deterioration or damage.

References

[1] **NBS ultraviolet radiometric standards,** W. R. Ott, Symposium on Measurements for the Safe Use of Radiation, *Natl. Bur. Stand. (U.S.), Spec. Publ. 456,* 107-110 (Mar. 1976).

[2] **Far UV radiometry—Survey of the NMS,** W. R. Ott, *NBSIR 75-941,* 69 pages (June 1977).

[3] **Vacuum ultraviolet radiometry. 3: The argon mini-arc as a new secondary standard of spectral radiance,** J. M. Bridges and W. R. Ott, *Appl. Opt.* **16,** 367-375 (1977).

[4] **Spectral radiance calibrations between 165-300 nm: An interlaboratory comparison,** J. M. Bridges, W. R. Ott, E. Pitz, A. Schulz, D. Einfeld, and D. Stuck, *Appl. Opt.* **16,** 1788-1790 (1977).
[5] **Spectral irradiance standard for the ultraviolet: The deuterium lamp,** R. D. Saunders, W. R. Ott, and J. M. Bridges, *Appl. Opt.* **17,** 593-600 (1978).
[6] **Vacuum ultraviolet spectral irradiance calibrations: Method and applications,** W. R. Ott, J. M. Bridges, and J. Z. Klose, *Optics Letters* **5,** 225-227 (1980).

(h) Photodetector calibrations.

Absolute spectral responsivity calibrations can be obtained by leasing one of the NBS Detector Response Transfer and Intercomparison Packages (DRTIP's).[1] This is a well-characterized radiometer that utilizes a silicon photodiode as the detector element. Its calibration is reported in units of A/W at a number of wavelengths in the 257-1064 nm range. A precision aperture is provided for calibrations in units of A cm^2/W. The duration of the lease is enough to allow for the transfer of the calibration to a laboratory's own in-house standards, and for the performance of specific diagnostic tests to check their capability in spectral response transfer measurements.

At present the DRTIP calibration[2] is based on electrical substitution radiometry[3] using cw laser lines as the monochromatic radiation source for the characterization measurements.[4] The absolute spectral response is reported at 10 nm intervals from 390 to 880 nm, and at several discrete wavelengths outside this range (257, 324, 338, 351, 364 and 1064 nm). In the 390 to 880 nm range the estimated uncertainty is 1.5 percent; elsewhere it is 5 percent. The radiometer covers a range of detector current from 10^{-3} to 10^{-6} A (full scale). This corresponds to a radiant power range of about 10^{-2} to 10^{-5} W. The lowest resolvable power depends on the resolution of the voltmeter used to read the radiometer output (10V = full scale).

At the time of this writing, the NBS method for photodetector calibration is undergoing considerable revision. This is due in large part to the recent development of a simple and accurate technique to measure directly the photon-to-electron conversion efficiency of a silicon photodiode.[5,6] Both the spectral range and accuracy of the calibration will be improved shortly. However, it is not possible at present to specify the extent of these expected improvements.

References

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[5] E. F. Zalewski and J. Geist, *Appl. Opt.* **19,** 1214 (1980).
[6] J. Geist, E. F. Zalewski, and A. R. Schaefer, *Appl. Opt.* **19,** 3798 (1980).

2. Photometric Standards

(a) Luminous intensity standards.

100-W (90-140 cd), 500-W (approximately 700 cd) and 1000-W (approximately 1400 cd) tungsten filament lamps with C-13B filaments in inside-frosted bulbs and medium bipost bases are supplied by NBS calibrated at either a set current or a specified color temperature in the range 2700-3000 K. Approximate uncertainties are 2 percent relative to the SI unit of luminous intensity and 1.5 percent relative to NBS standards.

(b) Luminous flux standards (geometrically total).

25-W vacuum tungsten lamps and 60-, 100-, 200-, and 500-W gas filled tungsten lamps submitted by customers are calibrated. Lamps must be base-up burning and rated at 120 V.

Approximate uncertainties are 2.5 percent relative to SI units and 1.5 percent relative to NBS standards.

Luminous flux standards for miniature lamps producing 6-400 lm are calibrated with uncertainties of 3 percent.

(c) Color temperature standards.

Airway beacon 500 W medium bipost lamps are calibrated for color temperature in the range 2000-3000 K with an uncertainty of 10 degrees.

Reference

[1] **Photometric calibration procedures,** V. I. Burns and D. A. McSparron, *Natl. Bur. Stand. (U.S.), Tech. Note 594-3,* (U.S. Government Printing Office, Nov. 1972).

B. Spectrophotometric Standards

1. Standards of Spectral Transmittance For Checking the Photometric Scale of Spectrophotometers[1]

These are either 30 mm polished glass disks or 51 mm polished glass squares, 2 to 3 mm thick, designated as cobalt blue, copper green, carbon yellow, and selenium orange (disks will be supplied unless otherwise specified). The report includes: (1) values of transmittance at 25 °C at certain wavelengths from 390 to 750 nm, (2) the estimated uncertainty of each value, and (3) the effect of temperature change on transmittance at each wavelength.

2. Holmium Oxide Glass Standards

Holmium oxide glass standards are available for checking the ultraviolet and visible wavelength calibrations of recording spectrophotometers having a bandpass less than 2 nm. These are made of polished Corning 3130 glass, 51×51 mm, 2.5 mm thick. The report includes a table of wavelengths of minimum transmittance.

3. Working Standards of Spectral Reflectance Factor

Working standards of spectral reflectance factor are now available as Standard Reference Materials (SRM's) 2015 and 2016. They are designed for use on spectrophotometers with 6° from perpendicular irradiation and diffuse reception. The standards consist of white structural Vitrolite glass, 102×102 mm, 8 mm thick or 38×51 mm, 11 mm thick. The report includes a table of spectral reflectance factors relative to perfect diffuser at every 10 nm. See chapter X, other NBS Services, for more information on SRM's.

Generally tests are based on correspondence regarding the exact nature of the requirements. Do not ship materials to the Bureau until arrangements for test have been completed. (See Appendix for NBS point of contact.)

4. Photographic Calibrations (e.g., Step Tablet Transmission Visual Density on Photographic and Radiographic Materials)

Diffuse transmission density is measured in accordance with ANSI Standard PH2.19-1959. Calibrated step tablets, both photographic and radiographic, are available through the Office of Standard Reference Materials as SRM 1008 and SRM 1001, respectively.

In special cases, measurements may be made by arrangement. ANSI Standard Diffuse Visual Transmission Density, Type VI-b, is measured on step tablets of 21 steps or less. Tablets submitted for calibration must be free of scratches, fingerprints, abrasions, and foreign matter and must have steps of uniform density. Tablets not suitable as standards are not accepted for calibration.

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[8] **The calibration of photographic edges at NBS,** R. E. Swing, *NBSIR 75-699,* 37 pages (Apr. 22, 1975). Order from NTIS as COM 75-11016.

[9] **Semiconductor measurement technology: Optical and dimensional measurement problems with photomasking in microelectronics,** J. M. Jerke, *Natl. Bur. Stand. (U.S.), Spec. Publ. 400-20,* 42 pages (Oct. 1975).

[10] **Interferometric lens testing,** J. M. Jerke and D. Nyyssonen, Air Force Avionics Laboratory (see [5]).

[11] **Development of dimensional measurement techniques from 1 to 10 micrometers and application to optical microscope measurements,** J. M. Jerke, *Meeting of Society of Photographic Scientists and Engineers, Proceedings* (Feb. 1975).

[12] **An improved photographic edge-artifact,** W. R. Smallwood and R. E. Swing, *NBSIR 76-1129,* 49 pages (Aug. 1976). Order from NTIS as PB274712.

5. Microcopy Resolution Test Charts

Microcopy resolution test charts conforming to ISO Standard 3334, NMA Standard MS104-1972, and MIL-M-9868D, are available through the Office of Standard Reference Materials (SRM 1010a).

6. Spectrophotometric Measurements

The measurements of spectral transmittance, spectral reflectance, or spectral reflectance factor covered under this item are intended primarily for information purposes and specimens so tested should not be accepted as "standards."

Measurements of spectral transmittance can be made for the wavelength region 0.19 to 2.5 μm. One or more of the following spectrophotometers will be used, depending upon the wavelength region to be covered: for transmittance, the NBS Reference Spectrophotometer [2], a Cary Model 14, or a General Electric Spectrophotometer. All measurements are made at room temperature unless otherwise requested.

Measurements of absolute spectral reflectance factors, and spectral specular reflectance, can be made for the wavelength region 0.25 to 2.5 μm. One or more of the following spectrophotometers will be used, depending upon the wavelength region to be covered: NBS Reference Spectrophotometer for Diffuse Transmittance and Reflectance; NBS Specular Reflectometer [5]; Cary Model 14 or General Electric. All of these instruments permit the [3,4] measurement of directional-hemispherical reflectance factor, while the first instrument also permits the measurement of 0°-45° reflectance factor. All measurements are made at room temperature.

Accuracy and precision estimates will be given, dependent upon the optical characteristics of the submitted specimens.

Measurements will be made on an actual cost basis, subject to a nominal minimum charge. Arrangements for measurements must be completed before shipment of specimens. The decision to perform the measurements and the instruments to be used will rest with NBS and refusal may be made after inspection of the specimens. Specimens not accepted for measurement will be returned, the cost of examination or the minimum charge will be applicable.

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C. Laser Power and Energy

The National Bureau of Standards develops and maintains the U.S. National Standards for measurement of laser power and energy. These standards are isoperibol type calorimeters which compare the absorbed laser radiation to an equivalent quantity of electrial energy. Limited calibration services and Measurement Assurance Programs (MAP's) are available for laser power and energy measurements.

1. NBS Laser Standards

The national standards for laser power and energy are three types of isoperibol type calorimeters. These calorimeters compare the absorbed laser radiation to an equivalent quantity of electrial energy. These calorimeters are maintained in a measurement system such that other laser power or energy meters can be calibrated against the national standards. The uncertainty of these calibrations is about 1 to 5 percent at the 99 percent level of confidence depending on the power (or energy) and wavelength at which the calibration is performed.

2. NBS Laser Power and Energy Dissemination Services

The laser power and energy measurement services consist of limited calibration of power or energy meters and Measurement Assurance Programs (MAP's). The MAP's are implemented by means of transfer standards which have been evaluated and characterized relative to the national standards. The characteristics of these transfer standards are well understood, and their associated accuracies are not significantly different from the accuracies associated with direct comparisons to national standards.

Reference

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CHAPTER IX

IX. Ionizing Radiation

The National Bureau of Standards carries out an extensive program of research directed towards state-of-the-art measurement of ionizing radiation. From this research, NBS establishes national standards, transfer instruments, measurement calibration services, and is developing measurement quality assurance testing. Measurement services are available, as described in the sections which follow, for neutron sources and dosimetry, for radioactivity, and for dosimetry of x-rays, gamma-rays, and electrons. Requests for additional information concerning NBS capabilities and services related to ionizing radiation should be directed to the points of contact listed in the Appendix.

A. Neutron Source and Dosimetry Standardization

The National Bureau of Standards provides neutron source calibrations as well as thermal neutron irradiations of foils and simple dosimeters in its thermal neutron density of 4000 neutrons/(cm^2 s). Due to an expansion in our neutron dosimetry and neutron reaction rate standardization programs, we are now able to offer sample irradiations in fast neutron spectra as well as in thermal-neutron fields of much greater intensity and purity.

The following neutron fields are available for special measurement services and fixed procedure calibrations:

(1) ^{252}Cf spontaneous fission neutrons: free-field fluence up to 10^{13} neutrons/cm^2 in $\sim$140 hours, specified to an accuracy of ± 2 percent (1σ) or better depending upon sample size and arrangement.

(2) ^{235}U cavity fission neutron field to a fluence of up to 2×10^{15} neutrons/cm^2 in 24 hours, specified to an accuracy of approximately ± 5 percent (1σ).

(3) A 24 keV Iron-Aluminum filtered beam to a fluence of 5×10^{11} neutrons/cm^2 to an accuracy of about 10 percent.

(4) A 2 keV Scandium filtered beam to a fluence of 2×10^{11} neutrons/cm^2 to an accuracy of about 5 percent.

(5) A 144 keV Silicon filtered beam to a fluence of 10^{12} neutrons/cm^2 to an accuracy of 10 percent.

(6) An external thermal neutron beam at the NBS reactor with free-field fluxes of up to 2×10^7 neutrons/(cm^2 s) specified to an accuracy of ± 3 percent (1σ) or better depending upon sample size.

(7) A cavity thermal neutron field with a near-isotropic neutron flux of about 10^{11} neutrons/(cm^2 s) specified to an accuracy of ± 5 percent (1σ) or better.

(8) Partially moderated californium fission neutrons with neutron field exposure parameters of 1.1×10^5 n/(cm^2 s) and 3 rem/hr at 30 cm from the center of the source.

(9) A 100 keV to 2 MeV variable energy monoenergetic Van de Graaff neutron beam with absolute accuracy of ± 2 percent, and fluence rate of 2×10^3 n/(cm^2 s) at 1 m.

(10) A 14.1 MeV monoenergetic Van de Graaff neutron beam with absolute accuracy of 2 percent and source strength of 10^8 n/s.

(11) A 2.6 MeV monoenergetic Van de Graaff neutron beam with absolute accuracy of 2 percent and source strength of 10^7 n/s.

1. Neutron Sources

The National Bureau of Standards provides a calibration service for natural standard neutron sources. By calibration and certification of such standards, accuracy and intercomparability are promoted in the measurements of neutron flux density which play an important part in current

research and neutron dosimetry. The service should be of particular assistance to those concerned with fundamental nuclear experiments, design and control of nuclear reactors, problems of protection from neutron radiation, and industrial applications of neutron sources.

The emission rates of neutron sources of 10^5 to a few times 10^8 neutrons/s calibrated against the NBS primary Ra-Be photoneutron standard source, NBS-I, by the manganous sulfate bath technique. The neutron emission rate for more intense sources up to about 10^{10} neutrons/s are calibrated by comparing their strength indirectly to the NBS standard source. The total uncertainty of the calibration is usually 1.2 percent to 1.7 percent, depending upon time and physical size of the neutron source.

The induced saturated manganese-56 activity of the bath is counted with two scintillation counters at a well-shielded remote location by continuously pumping a fraction of the bath volume to them. One scintillation counter samples the activity at the center of the volume and the second views a fraction of the same volume through a collimator. The first counter operates at about 100 counts/s for the standard source of about 10^6 neutrons/s; the second counter operates at about 4000 counts/s for sources of about 10^{10} neutrons/s but is close to background for the standard source. Relative counter efficiencies are obtained with an intermediate source of 10^8 neutrons/s.

The national primary standard neutron source, NBS-I, has been calibrated by independent absolute neutron absorption techniques and has been a focus for various international intercomparisons, the most recent under the sponsorship of the BIPM—see References. An effective recalibration of NBS-I against nubar for ^{252}Cf fission was reported in 1980—Ref. 1. The emission rate was determined to be $1.245 \times 10^6 \pm 0.8$ percent n/s as of September 1978 relative to a nubar of 3.766 ± 0.008. This is within 0.25 percent of the accepted value based on the absolute calibration of June 1961.

About two months should be allowed for source calibrations and advance arrangements must be made including the following information:

(1) A diagram showing the source location in the shipping container and instructions for removal of the source, if necessary.

(2) A description of any special markings on the source.

(3) The dimensions of the source, including the relative internal location of the active ingredients.

(4) The nature and amount of radioactive materials and the ratio of neutron producing ingredients.

(5) The kind of metal enclosing source and, if possible, the number of grams of each element.

(6) The date the source was sealed.

Sources accepted for calibration must be sealed, packed, and shipped in such a way that leakage and contamination will be avoided.

2. Personnel Protection Instrumentation

The National Bureau of Standards provides services for calibrating neutron measuring devices used for radiation protection purposes, and for determining their response as a function of neutron energy.

Routine calibrations may be done with ^{252}Cf spontaneous fission neutrons, or with ^{252}Cf neutrons moderated with heavy water. The former has a neutron spectrum very close to that of ^{235}U fission, while the latter has a spectrum which is roughly characteristic to that found inside containment at nuclear power plants. In either case, irradiations are performed in a large, low scatter room, where dose equivalent rates of approximately 10 mrem/hr to approximately 3 rem/hr are available.

To determine neutron response as a function of energy, four reactor beams are available: a thermal Maxwellian beam, and near-monoenergetic filtered beams with fixed energies of 2 keV, 24 keV, and 144 keV. For higher neutron energies, the NBS Van de Graaff is used to produce monoenergetic neutrons between 200 keV and 1.2 MeV, at 2.6 MeV, and at 14 MeV. While very intense beams are available thermal neutron energies (up to ~ 1 rem/hr in a 45 cm diam beam), the intensities of the filtered and Van de Graaff beams are much lower, ranging from 8 mrem/hr at 2 keV to 170 mrem/hr at 1 MeV, for a 20 cm diam beam.

3. Activation Foil Irradiation

Most calibrations and measurement reference procedures which involve activation foils are carried out under special measurement services because they exhibit very different experimental and energy response characteristics. Some attempt to establish a fixed-fee schedule for some of these calibrations is undertaken in this revision of NBS Calibration and Measurement Services.

Fission spectrum neutrons are available with two quite different sources. Spontaneous fission neutrons from californium-252 provide a well-understood spectra of neutrons at modest but accurately known intensities; the ^{235}U cavity fission source at the NBS reactor provides more intense but less well defined neutron fluxes ($\sim 10^3$ higher than with Cf) for irradiation of small threshold activation foils. See refs. [1], [2], and [14] through [18] for a description of application areas in neutron technology and measurement reference methods.

4. Thermal Density Standard

The NBS neutron physics laboratory continues to maintain a standard moderating geometry supplying a uniform partially thermal neutron density of about 4000 thermal neutrons/cm^2/s for indirect calibration of unknown thermal neutron densities by irradiation of gold foils. The standard thermal neutron density is produced by two 1 g Ra-Be (α,n) sources permanently fixed in a moderation geometry of paraffin and graphite. The exposure cavity is in graphite.

Four foils, no larger than 2×3.4 cm each, can be irradiated at one time. Information on the cadmium ratio of gold foils of various thicknesses in this density is provided with the calibration. Therefore, a separate cadmium-covered foil irradiation usually is not necessary but will be provided if requested. Foils usually are placed in the flux for one week and shipped by air mail to the laboratory requesting the calibration.

References

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[2] **Compendium of benchmark and test region neutron fields for pressure vessel irradiation surveillance; standard neutron spectra—Part I: ^{252}Cf spontaneous fission and Part II: ^{235}U thermal-neutron-induced fission,** Light-Water-Reactor, Pressure-Vessel-Surveillance Dosimetry Progress Report. *U.S. Nuclear Regulatory Commission Document NUREG/CR-0551, July-Sept. 1978* (Dec. 1978).

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B. Radioactivity

1. General Information

The Radioactivity Group at the National Bureau of Standards offers calibration services for over 50 radionuclides. Radioactivity calibrations include alpha-particle solid sources, beta-particle solutions, and gamma-ray solutions. In addition, some sources which do not meet the specifications for the individual calibration services may be calibrated on an "At-Cost" basis.

In order to offer such a broad range of services, NBS must place stringent limitations on the physical and chemical form and activity range of sources which can be accepted. To insure that these specifications are understood, it is essential that there be good communication between the technical personnel at the user facility and those at NBS (see paragraph 2). When planning to have a source calibrated, the user should discuss the following points with the technical contact at NBS:

Type of calibration and units used for reporting results

Often, more than one type of calibration is available for a given source. A cobalt-60 source, for example, may be calibrated in terms of total activity or gamma-ray emission rate. (Inquiries regarding the calibration of radioactive sources for exposure rate should be directed to the Dosimetry Group at (301) 921-2361.) Units to be used in reporting the result and some estimate of the total uncertainty in the calibration should also be discussed.

Source preparation, packaging and shipment

Details for these items are given in section 2. Two general requirements, however, apply to all sources submitted for calibration: (1) all shipments must conform to applicable Nuclear Regulatory Commission (NRC) and Department of Transportation (DOT) packaging and transport and, (2) source description, including approximate activity, must be provided in advance. The NBS Health Physics Section must approve in advance all proposed calibrations, and sources may be refused if the necessary information is not available.

Reports of Calibration

A Report of Calibration is sent on completion of a radioactivity calibration service. If the user has particular requirements for documentation of the calibration, these should be discussed with the technical contact at NBS before the services are performed.

2. Sample Preparation, Packaging and Shipping

All samples submitted for calibration must be chemically and physically stable. Paragraphs 4 and 5 describe the chemical form of solutions which are suggested for beta-particle emitters and gamma-ray emitters, respectively. A special lot of borosilicate-glass ampoules must be used for gamma-ray emitters. Empty ampoules are provided for this purpose. The volume of material in the ampoule should be 5.0 ± 0.2 ml.

Packaging for all sources must be in compliance with DOT and NRC regulations. Copies of regulations may be obtained from Operations Division, Office of Hazardous Materials, Department of Transportation, Washington, DC 20590. Postal regulations prohibit mailing radioactive materials which require a caution label under DOT regulations.

Alpha-particle solid sources must be supplied in special source holders such that the active area is not touched by any material. For sources to be measured in the 2 $\pi\alpha$ counter (Calibration 8.2 H) the diameter of the source must be less than 10 cm and that of the active surface less than 9 cm. For the 0.8 $\pi\alpha$ counter (Calibration 8.2 I), the maximum diameter is only 1.6 cm.

All sources arriving at NBS are checked by the Health Physics Section for radiation level and source integrity. Sources should be shipped to the attention of the technical contact at NBS, in care of:

Health Physics (Radioactivity Group)
Room B-131, Building 245
National Bureau of Standards
Quince Orchard and Clopper Roads
Gaithersburg, MD 20878

3. Calibrations of Alpha-Particle-Emitting Samples

Alpha-particle sources may be calibrated using the National Bureau of Standards 2 $\pi\alpha$ proportional counter [ref. 1], or the National Bureau of Standards 0.8 $\pi\alpha$ defined-solid-angle counter [ref. 2]. The former calibration is in terms of alpha-particle-emission rate into 2 π steradians, while the latter is in terms of total activity. A more detailed comparison of these counting systems is given in reference 3. Backscattering corrections for a variety of source-mount materials are discussed in the references below. The source thickness must be such that more than 99.5-percent of the emitted alpha particles have an energy greater than 400 keV. Further specifications for these calibration services are given in the table.

	Calibration 8.2H	Calibration 8.2I
Counting System	NBS $2\pi\alpha$ proportional counter	NBS $0.8\pi\alpha$ defined-solid-angle counter
Sources Calibrated For:	Alpha-particle-emission rate into 2π steradians	Total activity
Nominal Uncertainty ≠	1.5%	1.0%
Activity Range	1.5 Bq - 1.1×10^4 Bq	1.9×10^2 Bq - 1.1×10^4 Bq
Maximum Source Diameter	10 cm (9 cm for active surface)	1.6 cm

≠ The total estimated uncertainty will depend upon the activity level and source geometry.

* Test 8.2J includes calibration of the same source using both counting systems.

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[3] *NCRP Report 58, A Handbook of Radioactivity Measurements Procedures,* Section 3.7 **Alpha particle counting,** Mann, W. B. (ed.) National Council on Radiation Protection and Measurements, Washington (1978).

[4] **Study of the scattering correction for thick uranium-oxide and other α-particle sources—I: Theoretical,** L. L. Lucas and J. M. R. Hutchinson, *Int. J. Appl. Radiat. Isotopes,* **27,** 35 (1976).

[5] **Study of the scattering correction for thick uranium-oxide and other α-particle sources—II: Experimental,** J. M. R. Hutchinson, L. L. Lucas, and P. A. Mullen, *Int. J. Appl. Radiat. Isotopes,* **27,** 43 (1976).

4. Calibration of Beta-Particle Emitting Solution Sources

Due to low demand, the beta-particle calibrations described here will not be offered after December 1983.

Beta-particle-emitting solutions that conform to the physical, chemical and activity specifications for measurement are calibrated in either the National Bureau of Standards $4\ \pi\beta$ proportional counter or by liquid-scintillation counting. These specifications are shown in the table below.

Solutions should be approximately 5 ml in volume and flame-sealed in glass vials or ampoules.

No examination is made for beta-particle-emitting impurities, except in the case of phosphorus-32 where a half-life fit is made. If requested, the source will be examined for gamma-ray emitting impurities. This step may be essential for radionuclides such as promethium-147, which are often contaminated with other radionuclides.

Radionuclide	Counting System	Nominal[a] Uncertainty	Suggested Chemical Composition[b] Carrier	Solution
^{3}H	Liquid Scintillation	1.5%	H_2O	H_2O
^{14}C	Liquid Scintillation	2.5%	Na_2CO_3	0.001 M NaOH
^{32}P[c]	$4\pi\beta$ Proportional[d] counter	2.0%	H_3PO_4	0.0034 M H_3PO_4
^{36}Cl	Liquid Scintillation	2.0%	NaCl	H_2O
^{89}Sr	$4\pi\beta$ Proportional counter	3.0%	$SrCl_2$	1 M HCl
^{90}Sr-^{90}Y	Liquid Scintillation	2.5%	$SrCl_2$ YCl_3	1 M HCl
^{147}Pm	$4\pi\beta$ Proportional counter	3.0%	$PmCl_3$	1 M HCl
^{204}Tl	Liquid Scintillation	2.0%	$Tl(NO_3)_3$	1 M HNO_3

Suggested radioactivity concentration range 20 to 2000 kBq g^{-1}

[a] The total estimated uncertainty will depend upon the activity level and chemical form.
[b] The chemical composition is critical for these calibrations and should be discussed before sending the source.
[c] This calibration includes a half-life fit to determine the ^{33}P impurity.
[d] The design and operation of the NBS $4\pi\beta$ proportional counter are discussed in NCRP Report 58, A Handbook of Radioactivity Measurements Procedures, Section 3.5 "4π Proportional Counting," National Council on Radiation Protection and Measurements Report, Mann, W. B. (ed.), Washington (1978).

5. *Calibration of Gamma-Ray Solution Sources*

Tables 1 and 2 on the following pages list 39 radionuclides, solutions of which may be calibrated in the National Bureau of Standards "4π"γ ionization chamber. The sources must be submitted flame-sealed in the special ampoules provided by NBS. The operation of this type of chamber is described in NCRP Report 58, A Handbook of Radioactivity Measurements Procedures, Section 4.4 "Ionization Chambers," National Council on Radiation Protection and Measurements Report, Mann, W. B. (ed.), Washington (1978).

A. Radionuclides having half lives greater than 15 days (Calibration Service 8.2 C)

Table 1

Radionuclide	Nominal Uncertainty Limits of Ionization-Chamber Calibration[a]	Activity Range[b]	Suggested Chemical Form[c] Carrier	Suggested Chemical Form[c] Solution
^{22}Na	1.6%	0.4 – 40 MBq	NaCl	1 M HCl
^{46}Sc	0.8%	0.4 – 40 MBq	$ScCl_3$	1 M HCl
^{51}Cr	1.0%	2 – 60 MBq	$CrCl_3$	0.5 M HCl
^{54}Mn	1.2%	2 – 60 MBq	$MnCl_2$	1 M HCl
^{57}Co	0.8%	2 – 60 MBq	$CoCl_2$	1 M HCl
^{59}Fe	1.4%	0.4 – 40 MBq	$FeCl_3$	1 M HCl
^{60}Co	0.8%	0.4 – 40 MBq	$CoCl_2$	1 M HCl
^{65}Zn[d]	1.7%	2 – 60 MBq	$ZnCl_2$	1 M HCl
^{75}Se	2.4%	2 – 60 MBq	H_2Se0_3	1 M HNO_3
^{85}Sr	2.0%	2 – 60 MBq	$SrCl_2$	1 M HCl
^{88}Y	0.7%	0.4 – 40 MBq	YCl_3	1 M HCl
^{109}Cd-^{109m}Ag[d]	1.7%	2 – 60 MBq	$CdCl_2$	1.3 M HCl*
^{110m}Ag-^{110}Ag	0.9%	0.4 – 40 MBq	$AgNO_3$	1 M HNO_3
^{113}Sn-^{113m}In	3.0%	2 – 60 MBq	$SnCl_2$ or $SnCl_4$	4 M HCl
^{133}Ba	1.5%	2 – 60 MBq	$BaCl_2$	1 M HCl
^{134}Cs	1.0%	2 – 60 MBq	CsCl	1 M HCl
^{137}Cs-^{137m}Ba	1.5%	2 – 60 MBq	CsCl	1 M HCl
^{139}Ce	1.0%	2 – 60 MBq	$CeCl_3$	1 M HCl
^{141}Ce	2.0%	2 – 60 MBq	$CeCl_3$	1 M HCl
^{152}Eu	1.6%	0.4 – 40 MBq	$EuCl_3$	1 M HCl
^{154}Eu	0.8%	0.4 – 40 MBq	$EuCl_3$	4 M HCl
^{155}Eu	1.5%	2 – 60 MBq	$EuCl_3$	4 M HCl
^{169}Yb	2.5%	2 – 60 MBq	$YbCl_3$	0.1 M HCl*
^{195}Au	2.3%	2 – 60 MBq	$KAu(CN)_4$	10 gL^{-1} KCN* 10 gL^{-1} KCl*
^{203}Hg	1.4%	2 – 60 MBq	$Hg(NO_3)_2$	0.1 M HNO_3
^{226}Ra	1.1%	0.4 – 40 MBq	$RaCl_2$	1.4 M HCl

(a) The total estimated uncertainty will depend on the activity level and the chemical form.

(b) The ionization chamber is calibrated over a wide activity range for most radionuclides. If the source activity is not in the indicated range, this should be discussed in advance with the NBS technical contact.

(c) This information is based in large part on the NBS Standard Reference Materials for these radionuclides. For those radionuclides marked with an asterisk, the carrier should be discussed with the NBS technical contact.

(d) The calibrations for ^{65}Zn and ^{109}Cd-^{109m}Ag are in terms of gamma-ray-emission rate rather than activity.

B. Radionuclides having half lives less than 15 days (Calibration Service 8.2 D)

Table 2

Radionuclide	Nominal Uncertainty Limits of Ionization-Chamber Calibration[(a)]	Activity Range[(b)]	Suggested Chemical Form[(c)] Carrier	Solution
^{24}Na	0.8%	0.4 – 40 MBq	NaCl	1 M HCl
^{42}K	2.0%	2 – 60 MBq	KCl	1 M HCl
^{67}Ga	1.4%	0.4 – 40 MBq	$GaCl_3$	2 M HCl
^{99}Mo-^{99m}Tc	1.6%	2 – 60 MBq	Molybdate	4 M HNO_3
^{99m}Tc	1.5%	2 – 60 MBq	No carrier added/ pertechnetate	saline
^{111}In	1.3%	2 – 60 MBq	$InCl_2$	3 M HCl
^{123}I	1.5%	2 – 60 MBq	KI, Na_2SO_3	0.01 M LiOH*
^{131}I	1.3%	2 – 60 MBq	KI, Na_2SO_3	0.01 M LiOH*
^{140}Ba-^{140}La	3.4%	0.4 – 40 MBq	$Ba(NO_3)_2$, $La(NO_3)_3$	1 M HCl
^{197}Hg	2.4%	2 – 60 MBq	$Hg(NO_3)_2$	0.1 M HNO_3
^{198}Au	1.3%	2 – 60 MBq	$KAu(CN)_4$	10 gL^{-1} KCN* 10 gL^{-1} KCl
^{201}Tl	1.9%	2 – 60 MBq	$Tl(NO_3)_3$	0.9 M HNO_3
^{203}Pb	1.7%	2 – 60 MBq	$PbCl_2$	0.5 M HCl

[(a)] The total estimated uncertainty will depend upon the activity level and chemical form.

[(b)] The source activity should be in the indicated range when it arrives at NBS. The calibration scheduling must be coordinated with the NBS technical contact.

[(c)] This information is based in large part on the NBS Standard Reference Materials for these radionuclides. For those radionuclides marked with an asterisk, the carrier should be discussed with the NBS technical contact.

6. *Reports of Calibration*

Examples of Reports of Calibration provided for sources submitted for radioactivity calibration services will be provided upon request. The name of the organization for which the calibration was done normally appears at the top of the report. The random uncertainty is reported at the 99-percent confidence level and the total uncertainty is the linear sum of limits of the estimated systematic and random uncertainties. The estimated limits of systematic uncertainties are listed separately to allow the user to combine them with other systematic errors encountered in the use of the source.

C. Dosimetry of X-Rays, Gamma-Rays, and Electrons

1. *X-Ray and Gamma-Ray Measuring Instruments*

X-ray measuring instruments are calibrated in terms of exposure by a substitution method in an x-ray beam at a point where the exposure rate has been determined by means of a standard free-air ionization chamber. In order to provide instrument calibrations over a wide range of x-ray energies, many combinations of generating potential and filtration are available. These are listed in the Appendix under "Lightly Filtered X-Rays," "Moderately Filtered X-Rays," or "Heavily Filtered X-Rays." The calibration techniques requested should be appropriate to the instrument submitted.

Gamma-ray measuring instruments are calibrated in terms of exposure or absorbed dose at points in the collimated cobalt-60 and cesium-137 gamma-ray beams that have been standardized by means of graphite cavity chambers or a graphite calorimeter. Exposure rates and absorbed dose rates at the time of calibration are computed from the original beam standardization data and appropriate decay corrections. Ionization chambers submitted for an exposure calibration should have sufficient wall thickness to provide electron equilibrium for the gamma-ray energy selected. Ionization chambers submitted for an absorbed-dose calibration must be suitable for calibration in a phantom.

An ionization chamber and electrometer combination, with the electrometer marked in terms of exposure or absorbed dose, is calibrated by providing a dimensionless correction factor for the electrometer scale. An ionization chamber and electrometer combination with the electrometer marked in electrical units is calibrated as follows: (1) the chamber is calibrated in terms of exposure or absorbed dose per unit charge using an NBS electrometer, (2) the customer's electrometer is checked for linearity and charge measurement accuracy, and (3) the combination of chamber and electrometer is checked for consistency. An ionization chamber submitted without an electrometer is calibrated in terms of exposure or absorbed dose per unit charge. Calibration can be based on measurements for positive or negative polarizing potential, or on the mean of measurements for both positive and negative potentials, as requested. The ratio of ionization currents for full and half polarizing potentials and the corresponding ionization current, will be stated in the calibration certificate.

Ionization chambers are tested, prior to calibration, for leakage, radiation-induced leakage, stabilization time, short-term stability, recombination loss, connection to the atmosphere, and guard-electrode insulation (if applicable). Chambers found unsuitable for calibration will be returned with a statement of the reason for rejection. A charge may be made for time incurred in the tests. A statement of the performance specifications that the chambers are required to meet will be furnished on request to the address given in the Appendix.

All shipments to NBS of instruments for dosimetry calibration must be shipped in reusable containers. Even if properly packed, there can be no assurance that a calibrated instrument has maintained its calibration during shipment unless a method of verifying instrument stability has been established. Measurement should be made of the instrument response both before and after shipment, using a long-lived radioactive source and a highly reproducible measurement procedure. If desired, a small radioactive check source can be sent with the instrument when it is submitted for calibration. A long-term record of instrument stability using a suitable constancy check procedure is the most effective method for assuring the validity of the instrument calibration.

Irradiation of passive dosimeters, for readout by the customer, is available for the techniques listed in the Appendix. These irradiations are generally in terms of exposure; for passive dosimeters suitable for insertion in a phantom, irradiation in terms of absorbed dose can be provided by in-phantom irradiation using cobalt-60 gamma rays.

X-ray penetrameters, of the Ardran-Crookes type, can be calibrated using constant x-ray generating potentials up to 250 kV. These penetrameters are used for measurement of the generating potential of diagnostic x-ray units.

For details of the currently available services, see the Appendix under the title "X-Ray and Gamma-Ray Measuring Instruments."

References

[1] **Medical dosimetry standards program of the National Bureau of Standards,** R. Loevinger. *Proceedings of a Symposium on National and International Standardization in Radiation Dosimetry, Atlanta, GA, Dec. 5-9, 1977,* (International Atomic Energy Agency, Vienna, 1978). (This article provides references for earlier publications on NBS exposure and absorbed-dose standards.)

[2] **Exposure spectra from the NBS vertical-beam ^{60}Co gamma-ray source,** M. Ehrlich and C. G. Soares, *NBSIR 76-1117* (1976).

[3] **Spectrometry of a ^{60}Co gamma-ray beam used for instrument calibration,** M. Ehrlich, S. M. Seltzer, M. J. Bielefeld, and J. I. Trombka, *Metrologia* **12,** 169 (1976).

[4] **The graphite calorimeter as a standard of absorbed dose for cobalt-60 gamma radiation,** J. S. Pruit, S. R. Domen, and R. Loevinger, *J. Res. Natl. Bur. Stand. (U.S.),* **86,** No. 5, 495-502 (1981).

[5] **The photon-fluence scaling theorem for Compton-scattered radiation,** J. S. Pruitt and R. Loevinger, *Medical Physics* **9,** No. 2 (Mar./Apr. 1982).

[6] **Uncertainty in the delivery of absorbed dose,** R. Loevinger and T. P. Loftus, *Ionizing Radiation Metrology,*, International Course at Varenna, Italy, 1974, E. Casnati, ed., G-6, 459-473. Editrice Compositori, Bologna, 1977.

2. Gamma-Ray and Beta-Particle Sources

Sources submitted to the Bureau for dosimetry calibration are subject to the following conditions:

(a) Financial responsibility: Except for negligence by Bureau personnel, the Bureau assumes no responsibility for loss or damage to the sources while in its possession. The risk should be covered by insurance.

(b) Period of measurement: Inquiry should be made as to scheduling and turnaround time before the source is submitted.

(c) Preparation: Sources submitted for calibration must be sealed so that there can be no escape of any radioactive material, including any gaseous decay products. The sources, shielding, and packaging must be free of contamination. Contaminated or leaking sources cannot be measured and may cause considerable loss of time and damage to laboratory facilities. Sources must have been sealed for a sufficient time to be substantially in radioactive equilibrium with their decay products when these contribute to the emitted radiation.

(d) Packaging for shipment: Packages must be in compliance with the regulations of the Department of Transportation as detailed in CFR Title 49 and the regulations of the Nuclear Regulatory Commission as detailed in CFR, Title 10, Part 71. Copies of the Codes are available at the Government Printing Office, Washington, DC 20402.

All shipments to NBS of gamma-ray and beta-particle sources must be in reusable containers. A drawing showing the source container and a description of the method of source removal must be provided before the shipment is received at NBS. Postal regulations effectively preclude shipment of dosimetry sources by the Postal Service.

If the nature of the shipment requires a DOT Type B container subject to an NRC quality assurance program, documentation must be supplied to NBS certifying that the use of the container by NBS is part of the program of the shipper.

If the source is considered by the shipper to be in DOT Special Form, documentation to that effect must be furnished to NBS in order to allow NBS to return the source in compliance with 49CFR. The documentation must be in the form of a statement, signed by an authorized representative of the shipper, identifying the radionuclide and the source model and serial number or other identifying information, and certifying that the source is in DOT Special Form as prescribed by 49CFR173.398, and that the requisite certification and safety analysis records are on file with the shipper.

The shipment should ordinarily carry a label not in excess of DOT Yellow-II (surface exposure rate not in excess of 50 mR/h). If this is not possible, NBS should be notified that it will receive a DOT Yellow-III shipment.

(e) Possession of licensed materials: In submitting a source for calibration, it is necessary for the submitter to certify that he is duly authorized to possess the source under license by the applicable authority. In the case of individuals residing in a State that has entered into agreement with the Nuclear Regulatory Commission, State regulations are applicable to all sources including radium. In the case of other individuals, NRC regulations are applicable (radium is not licensed by the NRC). This certification may be by letter, by a suitable statement on the purchase order covering the calibration fee, or by a clear copy of the submitter's Possession License for the source.

Calibration in terms of exposure rate at 1 m is provided for gamma-ray sources of cobalt-60, cesium-137, and iridium-192; a similar service is planned for iodine-125. Radium is calibrated in terms of mass of equivalent radium content measured relative to the National Radium Standard through comparison of the gamma radiation from the specimen and the standard; where the details of encapsulation of the specimen are known, corrections can be made to obtain milligrams of radium content. Calibration in terms of absorbed dose rate is provided for suitable encapsulated beta-particle sources; the dose rate to a low-atomic-number material (graphite or plastic) is determined by measurement with an extrapolation chamber. For details of the currently available services, see the Appendix under the title "Gamma-Ray and Beta-Particle Sources."

References

[1] **Medical dosimetry standards program of the National Bureau of Standards,** R. Loevinger. *Proceedings of a Symposium on National and International Standardization in Radiation Dosimetry, Atlanta, GA, Dec. 5-9,1977* (International Atomic Energy Agency, Vienna, 1978). (This article provides references for earlier publications on NBS gamma-ray standards.)

[2] **Standardization of iridium-192 gamma-ray sources in terms of exposure,** *J. Res. Natl. Bur. Stand. (U.S.),* **85,** No. 1, 19-25 (1980).

3. Dosimetry of High-Energy Electron Beams

Dosimeters are provided twice a year to users requesting assistance with absorbed-dose measurements in high-energy electron beams. The dosimeters consist of ferrous sulfate (Fricke) solution in radiation-resistant silica-glass spectrophotometer cells. The user irradiates all but one of the three furnished dosimeters to between 50 and 80 Gy (5000 and 8000 rad) to water at electron energies between 5 and 50 MeV, employing the irradiation geometry (field size, phantom, position of dosimeter in phantom) given in the "Protocol for Dosimetry of High-Energy Electrons," Physics in Medicine and Biology **11**, 505 (1966).

After irradiation, the dosimeters are returned to the Bureau for spectrophotometric evaluation of the ferric-ion concentration in terms of absorbed dose in the phantom, using the G-value given in the Protocol. For details, see the Appendix under the title "Dosimetry of High-Energy Electron Beams."

References

[1] **Uniformity of high-energy electron-beam calibrations,** M. Ehrlich and P. J. Lamperti, *Phys. Med. Biol.* **14,** 305-314 (1969).

[2] **Proposed National Bureau of Standards program for the calibration of instruments used in high-energy electron and x-ray beams,** M. Ehrlich, *Ann. N.Y. Acad. Sci.* **161** (Article 1), 139 (1969).

D. Dosimetry for High-Dose Applications

1. Irradiation tests are available for customer-supplied dosimeters (such as solid radiochromic or liquid chemical types) or test samples that are sent to NBS, where they are packaged in appropriate material of thickness sufficient to approximate conditions of electron equilibrium. They are then irradiated in the NBS standard ^{60}Co calibration facility to specific agreed-upon absorbed dose values in the nominal "high-dose" range of $10–10^6$ grays ($10^3–10^8$ rads). The dosimeters may either be read and evaluated by NBS or sent back to the customer for their analysis and evaluation. Each dosimeter should not exceed dimensions of 1 cm $\times$ 2 cm $\times$ 5 cm.

2. NBS can provide sets of calibrated radiochromic dosimeters packaged in appropriate equilibrium material (such as polystyrene or aluminum). The sealed packaged dosimeters are sent to the customer for irradiation to nominal agreed-upon absorbed dose levels in a prescribed geometrical arrangement. The unopened packaged dosimeters are then returned to NBS to be read and evaluated. The absorbed dose range that is suitable for use with the radiochromic dosimeters is 1 to 600 kGy (0.1 to 60 Mrad) in water, silicon, aluminum, graphite, or certain plastics.

Spectrophotometric analysis of irradiated dosimeters may be done at several specific ultraviolet or visible optical wavelengths or as a spectral scan over an appropriate wavelength region of interest.

Other tests, such as the temperature dependence of the radiation response of a given type of radiochromic dosimeter system, can be provided as special measurement services.

For details of the services, see the Appendix under the title "8.6 Dosimetry for High-Dose Applications."

References

[1] **A national standardization programme for high-dose measurements,** W. L. McLaughlin, *Technical Report No. 205,* pp. 17-32, IAEA, Vienna (1981).

[2] **Dosimetry for industrial radiation processing,** W. L. McLaughlin, J. C. Humphreys, and A. Miller, *Natl. Bur. Stand. (U.S.), Spec. Publ. 609* (1981).

[3] **Dye film dosimetry for radiation processing,** J. C. Humphreys and W. L. McLaughlin, *IEEE Trans. Nucl. Sci.* **NS-28,** No. 2, pp. 1797-1801 (Apr. 1981).

[4] **The measurement of absorbed dose and dose gradients,** W. L. McLaughlin, *Radiat. Phys. Chem.* **15,** pp. 9-38 (1980).

[5] **Dosimetry standards for industrial radiation processing,** W. L. McLaughlin, *National and International Standardization of Radiation Dosimetry,* **1,** IAEA, Vienna (1978).

CHAPTER X

X. Other NBS Services

The National Bureau of Standards provides many other services in addition to the calibration and testing programs to which this publication is primarily addressed.

A. Standard Reference Materials

The Standard Reference Materials program of the National Bureau of Standards provides science, industry, and government with a central source of well-characterized materials certified for chemical composition, or for some chemical or physical property. These materials are designated Standard Reference Materials (SRM's) and are used to calibrate and evaluate measuring instruments, methods, and systems or to produce scientific data that can be referred readily to a common base. Approximately 900 SRM's currently available from NBS are described in the Catalog of NBS Standard Reference Materials, NBS Special Publication 260, and its supplements.

All of the Standard Reference Materials (SRM's), Research Materials (RM's), and Special Reference Materials (GM's) listed in SP260 bear distinguishing names and numbers by which they are permanently identified. Each SRM, RM, or GM bearing a given designation is of identical characterization with every other sample bearing the same designation, within the limits required by the use for which it is intended; or if necessary, it is given a serial number and an individual calibration.

New SRM's are prepared each year and are announced through supplements to SP260 as well as directly to prospective users who have requested such notification. Price lists are issued periodically and provide a complete list of the available SRM's, and their prices.

Areas in which materials are available are listed below. Request for additional information or copies of SP260 should be addressed to the Office of Standard Reference Materials, at the address shown in the Appendix.

Standard Reference Materials (SRM's)

Chemical Composition Standards

Steels (chip form): Plain carbon, low and high alloys, stainless and tool.

Steels (granular form): Special ingot irons, low alloy, stainless, speciality, high-temperature alloys, and tool.

Steelmaking Alloys

Cast Irons (chip form)

Cast Steels, White Cast Irons, Ductile Irons, and Blast Furnace Irons (solid form)

Nonferrous Alloys (chip form): Aluminum, cobalt, copper, lead, magnesium, nickel, nickel oxide, selenium, tin, titanium, zinc, and zirconium

Nonferrous Alloys (solid form): Copper, lead, nickel, tin, titanium, zinc, and zirconium

Gases in Metals

High-Purity Metals

Electron Probe Microanalytical Standards

Primary, Working, and Secondary Standard Chemicals

Microchemical Standards

Clinical Laboratory Standards

Biological Standards

Environmental Standards: Gases, liquids, solids, permeation tubes, and trace elements in fossil fuels

Industrial Hygiene Standards

Forensic Standards

Metallo-Organic Compounds

Fertilizers

Ores

Cements

Minerals, Refractories, Carbides, and Glasses

Trace Element Standards

Nuclear Materials: Plutonium and uranium assay and isotopic standards, neutron density standards, and fission track glass standards

Isotopic Reference Standards

Physical Property Standards

Ion Activity Standards: pH and pD standards, and ion selective electrodes

Mechanical and Metrology Standards: Coating thickness, glass, elasticity, density, and polymer

Heat Standards: Superconductive thermometric fixed point devices, freezing points, melting points, calorimetry, differential thermal analysis, vapor pressure, thermal conductivity, thermal expansion, thermocouple materials

Magnetic Standards: Magnetic susceptibility

Optical Standards: Spectrophotometry, reflectance, refractive index

Radioactivity Standards: Alpha-particle, beta-particle, gamma-ray, and electron capture standards, contemporary standard for carbon 14 dating laboratories, environmental standards, low energy photon sources, and solution standards

Metallurgical

Mossbauer

X-Ray Diffraction

Permittivity

Reference Fuels

Resistivity

Engineering Type Standards

Standard Rubber and Rubber-Compounding Materials

Reference Magnetic Computer Tapes

Sizing Standards: Glass spheres for particle size, turbidimetric and fineness (cement)

Color Standards: The ISCC-NBS centroid color charts, light-sensitive papers, light-sensitive plastic chips

X-Ray and Photographic Standards

Surface Flammability Standards

Smoke Density Chamber Standards

Water Vapor Permeance

Tape Adhesion Testing Standard

Research Materials (RM's)

High-Purity Materials, Phosphors, Glass Fibers for Miro-Chemical Analysis

Special Reference (GM's)

Hydrogen in Steel, Cellular Plastics, and DTA Temperature Standards

B. Proficiency Sample Programs

In 1936, the first reference sample program was initiated for cement as part of the NBS Research Associate program of the Cement Reference Laboratory of the American Society for Testing and Materials (ASTM) Committee C-1. In 1966, this program was revised to essentially its present form wherein two pairs of samples for physical tests and two pairs of samples for chemical analyses are distributed each year. Similar programs for masonry cement, blended cement, bituminous, bituminous concrete, soils, aggregates, and portland cement concrete were then established in rapid succession, the last in 1978. These programs are under the sponsorships of ASTM and the American Association of State Highway and Transportation Officials (AASHTO).

In 1969 a bimonthly collaborative reference program for paper and board testing was sponsored by the Technical Association of the Pulp and Paper Industry and a program for control of the quality of shipping container components was established for the Fourdrinier Kraftboard Institute. This latter program involves monthly reports but weekly testing by the participants. A quarterly program for the rubber industry was developed in 1970 with the help of ASTM Committee D011, and a color and appearance program, of interest to many industries and users, was sponsored by the Manufacturers Council on Color and Appearance. This quarterly program presently includes tests for gloss, color, and color difference.

C. National Voluntary Laboratory Accreditation Program

Established in 1976 by the Secretary of Commerce (15 CFR Part 7), the National Voluntary Laboratory Accreditation Program (NVLAP) is designed to accredit testing laboratories at their request in areas of product testing in which a need for a laboratory accreditation program has been determined. NVLAP has accredited approximately 100 laboratories for competence in performing certain specific tests on thermal insulation, concrete, or carpet. Other programs for acoustical testing services, electromagnetic calibration services, solid fuel room heaters, and radiation dosimetry are being developed. Requests to establish NVLAP programs in other testing areas are welcome. The laboratory evaluation process leading to accreditation is conducted by NBS and generally includes (1) submittal of written information, (2) periodic on-site examinations, and (3) participation in proficiency sample testing.

For additional information including an application for accreditation under any of the established programs, write the NBS NVLAP Coordinator, Technology Building, Room B06, Washington, DC 20234.

D. National Center for Standards and Certification Information

The National Center for Standards and Certification Information (NCSCI) maintains a reference collection of some 240,000 engineering standards issued by U.S. technical societies, professional organizations, and trade associations; State purchasing offices; U.S. civilian and military agencies; and foreign national and international standardizing bodies. The collection is open to the public Monday through Friday from 8:30 a.m. to 5:00 p.m.

NCSCI publishes general and special indices of standards. Information services include responses to inquiries on specifications, test methods, or recommended practices for a given item, product, or material. Inquirers are referred to the appropriate source to obtain copies of standards. NCSCI neither sells nor distributes standards.

Inquiries or requests for additional information should be directed to the address listed in the Appendix.

E. Standard Reference Data

The National Standard Reference Data System (NSRDS) is a nationwide program established to make critically evaluated data in the physical sciences available to the technical community. It publishes compilations of critically evaluated data, critical reviews and bibliographies. A complete

listing of the publications of the NSRDS is available from the Office of Standard Reference Data (OSRD). The OSRD responds to queries within the scope of the program by providing references, referrals, documentation, or data, as available. The program's newsletter is available on request. Inquiries or requests for further information should be directed to the address listed in the Appendix.

F. Technical Information and Publications

The Technical Information and Publications Division maintains a limited correspondence and inquiry service on the technical activities of the National Bureau of Standards. Inquiries of a general nature and not covered by the services listed above should be directed to Technical Information and Publications Division, National Bureau of Standards, Washington, DC 20234.

G. NBS Measurement Seminars

Each year NBS holds several measurement seminars and workshops. Participation is open to a limited number of persons from measurement and standards laboratories who meet appropriate prerequisites relating to education, work experience, and current professional activity. Seminars last from 1 to 5 days and comprise lectures, group discussions, and/or laboratory demonstrations. The seminars are announced in the semiannual SP250 Appendix.

H. Office of Weights and Measures

The role of the Office of Weights and Measures (OWM) is to provide leadership and those technical resources that will assure accuracy of the quantity representations in all commercial transactions for all buyers and sellers in the United States, and to promote a uniform national weights and measures system.

In fulfilling its mission, OWM engages in a wide range of activities, including providing the secretariat and other technical input for the National Conference on Weights and Measures. Foremost is the assistance offered to the States in the following areas:

(1) The development of model weights and measures laws and technical regulations for the States and local jurisdictions.

(2) The development and dissemination of design and performance specifications for various standards of mass, length, and capacity for use as State and local reference, laboratory, and field standards.

(3) The design of testing equipment and the development of testing procedures for weighing and measuring devices.

(4) The examination of prototype commercial weighing and measuring devices and equipment submitted by manufacturers for conformance with Handbook 44 requirements.

(5) The calibration of State standards. State weights and measures laboratories perform calibrations and tolerance tests of mass, volume, and length secondary standards for industry and service agencies.

(6) The conduct of technical training in weights and measures enforcement and laboratory metrology. OWM serves as a central resource for metric coordination for the states and local jurisdictions, and prepares and disseminates information on standards, testing equipment technical procedures, technical investigations, and standard practices.

Prototype Examination of Commercial Weighing and Measuring Devices, Reference and Field Standards

OWM operates a Prototype Examination Program which provides for an evaluation of (1) prototype weighing and measuring devices to determine compliance with the requirements of NBS Handbook 44, "Specifications, Tolerances, and Other Technical Requirements for Commercial Weighing and Measuring Devices," and (2) standards to determine compliance with the requirements of NBS Handbooks 105-1, 105-2, 105-3, "Specifications and Tolerances for Reference Standard and Field Standard Weights and Measures." This program may be used by manufacturers and weights and measures officials in determining the acceptability of devices for commerical use or the suitability of reference and field standards.

Equipment will be examined at any stage of development on request. The examination may be made in the laboratories of the National Bureau of Standards, at the factory, or in the field.

When a device is found to be in compliance with Handbook 44, or standards in compliance with H105-1, H105-2, or H105-3, a report of test will be issued to the submitter. When equipment is found not to be in compliance, the submitter will be notified by letter and the discrepancies fully explained. The equipment may then be modified and resubmitted. If it is the submitter's decision not to make any modifications, a report of test will be issued detailing the areas where discrepancies exist. Copies of all reports of test will be sent to each state weights and measures office.

To obtain a prototype examination:

Address a letter giving a reasonably complete description of the equipment, its operating characteristics and instructions, and its intended application, model number, capacity, size, and shipping weight, to the Office of Weights and Measures, National Bureau of Standards, Washington, DC 20234, requesting an examination.

I. Structural Engineering—High Capacity Testing Machine

The research and testing facilities for structural engineering include a 53-MN (12 million-lbf) capacity universal testing machine believed to be the largest in the world. A significant addition to the nation's facilities for research and testing in the field of large structures, this unique machine is available to do work for the entire technological community upon consideration of requests on a case-by-case basis. This hydraulically operated machine is a vertical, four-screw type with the main fixed platen flush with the floor. It is capable of applying 53 MN (12×10^6 lbf) in compression to test specimens up to 17 m (58 ft) in height and 27 MN (6×10^6 lbf) in tension to specimens up to 16 m (53 ft) in length. To extend the versatility of the machine, the reinforced concrete foundation incorporates a floor tie-down system which can accommodate test specimens for transverse loading up to 27 m (90 ft) in length. Calibration of all load ranges indicates that they exhibit error generally no greater than 0.5 percent of the applied load. A more detailed description of this facility is presented in NBS Special Publication 355.

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